

# REPORT 51



**SWEEP  
SWEEP**

SOIL AND WATER  
ENVIRONMENTAL  
ENHANCEMENT PROGRAM



**PAMPA**

PROGRAMME D'AMELIORATION  
DU MILIEU PEDOLOGIQUE  
ET AQUATIQUE

Canada

 Ontario



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## **SWEEP**

*is a \$30 million federal-provincial agreement, announced May 8, 1986, designed to improve soil and water quality in southwestern Ontario over the next five years.*

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### **PURPOSES**

*There are two interrelated purposes to the program; first, to reduce phosphorus loadings in the Lake Erie basin from cropland run-off; and second, to improve the productivity of southwestern Ontario agriculture by reducing or arresting soil erosion that contributes to water pollution.*

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### **BACKGROUND**

*The Canada-U.S. Great Lakes Water Quality Agreement called for phosphorus reductions in the Lake Erie basin of 2000 tonnes per year. SWEEP is part of the Canadian agreement, calling for reductions of 300 tonnes per year — 200 from croplands and 100 from industrial and municipal sources.*

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## **PAMPA**

*est une entente fédérale-provinciale de 30 millions de dollars, annoncée le 8 mai 1986, et destinée à améliorer la qualité du sol et de l'eau dans le Sud-ouest de l'Ontario.*

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### **SES BUTS**

*Les deux buts de PAMPA sont: en premier lieu de réduire de 200 tonnes par an d'ici 1990 le déversement dans le lac Erie de phosphore provenant des terres agricoles, et de maintenir ou d'accroître la productivité agricole du Sud-ouest de l'Ontario, en réduisant ou en empêchant l'érosion et la dégradation du sol.*

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### **SES GRANDES LIGNES**

*L'entente entre le Canada et les États-Unis sur la qualité de l'eau des Grands Lacs prévoyait de réduire de 2 000 tonnes par an la pollution due au phosphore dans le bassin du lac Erie. PAMPA fait partie de cette entente qui réduira cette pollution de 300 tonnes par an — 200 tonnes provenant des terres agricoles et 100 tonnes provenant de sources industrielles et municipales.*

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TECHNOLOGY EVALUATION AND DEVELOPMENT SUB-PROGRAM

LOSS OF NITROGEN BY MICROBIAL  
DENITRIFICATION, NITRIFICATION, SURFACE  
AND TILE RUNOFF: RELATION TO  
TILLAGE METHOD

FINAL REPORT

May, 1992

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## EXECUTIVE SUMMARY

Concerns over contamination of natural water systems and rising costs of production in the agriculture industry have led to increasing use of conservation tillage methods as a means of reducing these effects. Reduced tillage, however, also affects water movement, aeration and N-transformations in soils. A simplified N-cycle diagram for soils is shown in Figure 1. The research described in this report was focused on several of these aspects as summarized below:

### 1.1 NITRATE LOSS IN SURFACE AND TILE RUNOFF WITH CONSERVATION AND CONVENTIONAL TILLAGE

Nitrate concentrations and total volume of surface and tile runoff from conventional (moldboard plow) tillage (CT), no-tillage (NT), ridge tillage (RT) all planted in continuous corn, and Kentucky bluegrass (BG) treatments, were measured over three years, 1989 to 1991. All corn tillage treatments received a total of 178.6 kg N ha<sup>-1</sup> annually over the growing season. The volume of water drained through the tiles in the corn tillage systems always exceeded the volume in surface runoff, typically by factors of 2 to 4. Tile outflow was greatest from the CT treatments, least from BG and approximately equal from RT and NT treatments in 1989 and 1990. Concentrations of NO<sub>3</sub><sup>-</sup> in tile water from CT, RT and NT treatments exceeded the maximum recommended safe limit of 10 mg N L<sup>-1</sup> in 79% of runoff events with flow-weighted concentrations between 12 and 17 mg N L<sup>-1</sup> in 1989 and 1990. Flow-weighted NO<sub>3</sub><sup>-</sup> concentrations were only 1.2 and 2.6 mg N L<sup>-1</sup> from BG in 1989 and 1990 respectively. The total NO<sub>3</sub><sup>-</sup> lost in tile water in 1989 was 18, 14, 14 and 1 kg N ha<sup>-1</sup> from the CT, RT, NT and BG treatments, respectively, whereas in 1990 there was 29, 20, 20 and 3 kg N ha<sup>-1</sup> lost from the CT, RT, NT and BG treatments. Nitrate losses in surface runoff were lower than tile runoff with maximums of 2.6 kg N ha<sup>-1</sup> for the RT and NT treatments in 1989 and 5.5 kg N ha<sup>-1</sup> for the RT treatment in 1990. In 1989 and 1990, both RT and NT treatments had greater

yields and N-uptake than the CT treatment. A serious drought in 1991 limited corn yield, N uptake and  $\text{NO}_3^-$  loss.

## 1.2 BACKGROUND AND POTENTIAL DENITRIFICATION VARIATION WITH DEPTH UNDER CONSERVATION AND CONVENTIONAL TILLAGE

Background and potential denitrification was measured in Brookston clay soil at depths to 0.9 m under several conservation tillage plots and a conventional moldboard plow tillage plot. The objective was to identify possible effects of the various tillage treatments on denitrification and on  $\text{NO}_3^-$  loss. Background denitrification ( $\text{NO} + \text{N}_2\text{O}$ ) was estimated in intact cores in 1989 and 1990 using a gas flow-through system which permitted net  $\text{NO}$  and  $\text{N}_2\text{O}$  production rates to be measured. Rates decreased with increasing depth under all tillage treatments but no correlation was evident between background denitrification and tillage, perhaps due to the large spatial variability observed. Potential denitrification estimates were made using excess added  $\text{NO}_3^-$  and the  $\text{C}_2\text{H}_2$  blockage method (Yoshinari, *et al*, 1977). Estimates were obtained in 5 cm increments to a depth of 0.9 m. In all cases the top 5 cm increment showed highest potential for denitrification. Among the tillage treatments the highest potential was with the no-till Kentucky bluegrass plot and intermediate potentials in ridge till and no-till corn plots and lowest in the conventional till plot. Carbon dioxide production,  $\text{NO}_3^-$  and  $\text{NH}_4^+$  levels followed the same pattern with depth. The relatively low denitrification potential below the uppermost soil layer suggests that in these plots denitrification would not be expected to greatly ameliorate  $\text{NO}_3^-$  loss by leaching.

## 1.3 NITRIC OXIDE AND NITROUS OXIDE PRODUCTION: WATER AND OXYGEN EFFECTS

This study was designed to determine the effects of water and  $\text{O}_2$  on the speciation of denitrification gases ( $\text{NO}$  and  $\text{N}_2\text{O}$ ). Nitric oxide was found to be the principal end product from soil

incubated under low moisture conditions, whereas the relative amount of  $N_2O$  increased under wetter moisture regimes. The total amount of  $NO$  plus  $N_2O$  produced increased with increasing water content for the Brookston clay loam whereas it peaked at 15% water content with the Fox sandy loam. The decrease in  $NO$  plus  $N_2O$  at higher water contents was probably the result of the subsequent reduction of  $N_2O$  to  $N_2$  in the Fox sandy loam soil. The residence time of the denitrification gases in the soil increased with increasing water content, hence facilitating the subsequent conversions of  $NO$  to  $N_2O$  and  $N_2$ . The thickness of the water film surrounding the microbes affected both the diffusion of  $O_2$  through the water and into the microbes as well as the diffusion of denitrification gases ( $NO$ ,  $N_2O$ , and  $N_2$ ) from the microbes into the atmosphere. In the sandy loam soil,  $O_2$  content and soil water affected both the amount and species of evolved denitrification gases. Oxygen was more effective in decreasing  $NO$  production at lower than at higher water contents.

## 2.1 IMPLICATIONS

Although conservation tillage (RT and NT) decreased the concentration and total loss of  $NO_3^-$ , the concentrations generally exceeded the  $10 \text{ mg N L}^{-1}$  recommended limit. Further reduction could perhaps be achieved through use of cover crops, intercrops or controlled drainage systems. In conservation tillage systems, particularly RT, losses of  $N$  by denitrification would likely be reduced if nitrogen fertilizer was added below the surface 5 cm zone. Since tillage influences water infiltration and storage and the aeration status of the soil, the overall denitrification rate is affected as well as the ratio of  $NO:N_2O$ . Thus tillage indirectly affects the environmental impacts of these important atmospheric trace gases, and also contributes to the observed large spatial variability in flux of these gases from soils. Greater levels of  $NO$  evolve from drier soils and relatively greater levels of  $N_2O$  from wetter soils. Under all tillage systems both background and potential denitrification decreased

markedly with depth reflecting low denitrifier populations below the surface layer. Hence in the plots used in this study, denitrification would not be expected to greatly ameliorate loss of  $\text{NO}_3^-$  by leaching.

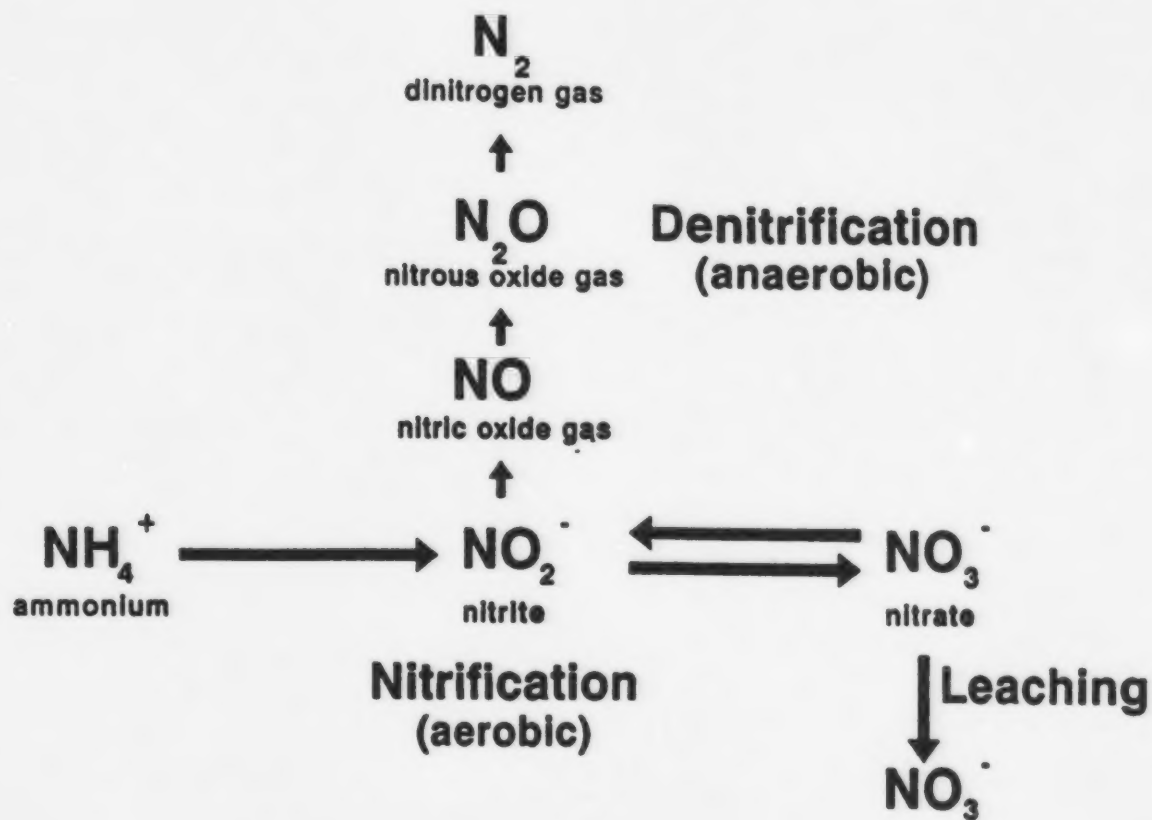


Figure 1. A simplified N cycle diagram for soils.



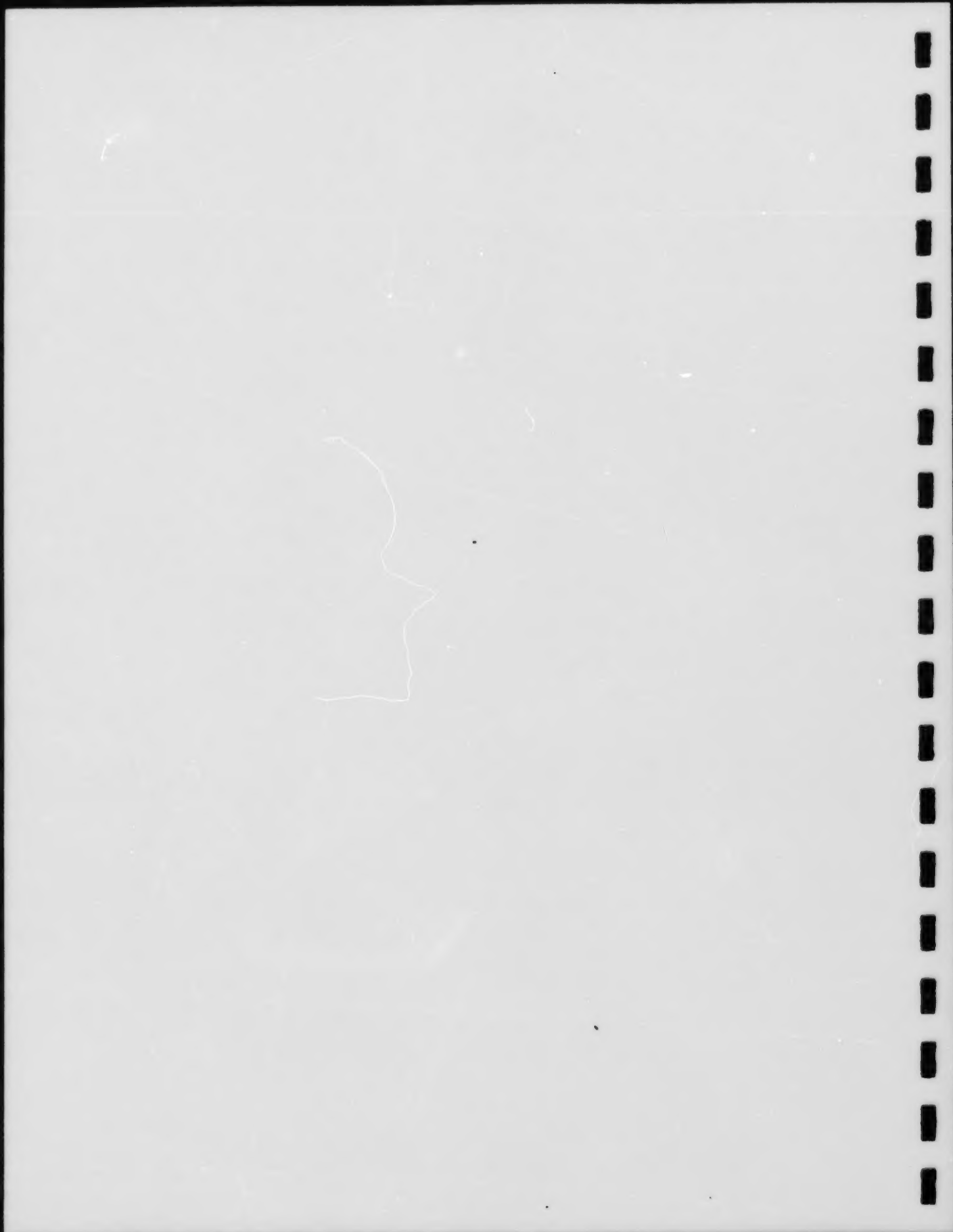
# LOSS OF NITROGEN BY MICROBIAL DENITRIFICATION, NITRIFICATION, SURFACE AND TILE RUNOFF: RELATION TO TILLAGE METHODS

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# 1 NITRATE LOSS IN SURFACE AND TILE RUNOFF WITH CONSERVATION AND CONVENTIONAL TILLAGE

## 1.1 INTRODUCTION

Nitrate contamination of surface and tile runoff water from intensive agricultural production systems has become a serious environmental and economic concern. Contaminated waters contribute to eutrophication of lakes and streams. In addition since some municipalities use surface waters for human consumption, the  $\text{NO}_3^-$  content in these waters must be less than  $10 \text{ mg N L}^{-1}$ . Nitrate can be readily converted to  $\text{NO}_2^-$  in the body which has been implicated in two major health problems, blue-baby syndrome (methaemoglobinaemia) and stomach cancer.

Nitrate concentrations in tile water under a corn crop fertilized with  $285 \text{ kg N ha}^{-1}$  were seldom less than  $10 \text{ mg N L}^{-1}$  and usually within  $20\text{-}30 \text{ mg N L}^{-1}$  range with annual losses ranging between  $18\text{-}70 \text{ kg N ha}^{-1}$  depending on tile drain spacing (Kladivko et al., 1991). The concentration of  $\text{NO}_3^-$  in tile runoff and the amount of  $\text{NO}_3^-$  loss was proportional to the amount of N fertilizer applied to the soil (Baker and Johnson, 1981). In particular, Baker and Johnson (1981) found that N fertilization rates of corn between  $90\text{-}100 \text{ kg N ha}^{-1}$  resulted in flow-weighted N concentrations of  $20 \text{ mg N L}^{-1}$  in tile runoff with a total loss of  $27 \text{ kg N ha}^{-1}$  whereas N fertilizer rates between  $240\text{-}250 \text{ kg N ha}^{-1}$  resulted in flow-weighted  $\text{NO}_3^-$  concentrations of  $40 \text{ mg N L}^{-1}$  and total N losses of  $48 \text{ kg N ha}^{-1}$ . Prunty and Montgomery (1991) found that flow-weighted  $\text{NO}_3^-$  concentrations from lysimeters were  $8.6 \text{ mg N L}^{-1}$  for low N management ( $95 \text{ kg N ha}^{-1}$  added fertilizer) and  $12.3 \text{ mg N L}^{-1}$  for high N management ( $145 \text{ kg N ha}^{-1}$ ) corn production systems. However, the addition of  $95 \text{ kg N ha}^{-1}$  was below the maximum economical rate of fertilizer use for yield. In many other studies with corn production systems the concentration of  $\text{NO}_3^-$  in tile runoff exceeded the  $10 \text{ mg N L}^{-1}$  limit for potable water. For example the range of  $\text{NO}_3^-$  concentrations in leachate from lysimeters ranged from  $10 \text{ mg N L}^{-1}$  in clay soils to  $50 \text{ mg N L}^{-1}$  in the sandy soils (Bergstrom and Johansson, 1991).

Annual N losses from lysimeters seeded with spring Barley and fertilized with 100 kg N ha<sup>-1</sup> were 20 kg N ha<sup>-1</sup> for clay soils, 25-40 kg N ha<sup>-1</sup> for loamy soils and 65 kg N ha<sup>-1</sup> or less for sandy soils. Rainfall and irrigation also contribute to the extent and timing of NO<sub>3</sub><sup>-</sup> loss. In several studies increases in NO<sub>3</sub><sup>-</sup> concentration in tile runoff appeared within 2-3 months after N was applied (Hubbard et al., 1984; Baker and Johnson, 1981) and persisted up to 3 years following the last application of N fertilizer.

Conservation tillage systems affect water movement in soil systems. There were greater amounts of NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> in surface runoff from a conventionally tilled watershed than from a no-tillage watershed however the losses in both watersheds were very low with a maximum of 0.27 kg NH<sub>4</sub><sup>+</sup>-N ha<sup>-1</sup> yr<sup>-1</sup> and 0.638 kg NO<sub>3</sub><sup>-</sup>-N ha yr<sup>-1</sup> over a 3 year period (Angle et al., 1984). Although conservation tillage systems decreased NO<sub>3</sub><sup>-</sup> losses in surface runoff they may have a deleterious effect on subsurface NO<sub>3</sub><sup>-</sup> concentration. Angle et al. (1984) postulated that most of the losses of NO<sub>3</sub><sup>-</sup> from the watershed was due to subsurface groundwater flow and not surface runoff.

Since NO<sub>3</sub><sup>-</sup> contamination of drainage tile water has been found to be a serious problem in intensive corn production systems (Kladivko et al., 1991; Baker and Johnson, 1981; and Prunty and Montgomery, 1991) it is important to evaluate nutrient transport under varying tillage systems. Therefore, the objective of this study was to determine if conservation tillage systems (ridge and no-tillage) affected the volume, concentration and total amount of NO<sub>3</sub><sup>-</sup> lost in both surface and tile runoff as compared to a conventional tillage (moldboard) practice. The amount of nitrogen assimilated by the plant would also affect the amount available for leaching losses. Therefore, the effect of conservation tillage systems (ridge tillage and no-till) on corn grain yields and N uptake were also evaluated.

## 1.2 MATERIALS AND METHODS

The plots were established in 1983 at the honourable Eugene Whelan Experimental Farm, Woodslee, Ontario. The soil used in this experiment was a Brookston clay loam, a poorly drained lacustrine soil (clayey, mixed, mesic Typic Haplaquolls). The average textural analyses for this soil is 290 g kg<sup>-1</sup> sand, 350 g kg<sup>-1</sup> silt, and 360 g kg<sup>-1</sup> clay.

Ammonium, NO<sub>3</sub><sup>-</sup> and NO<sub>2</sub><sup>-</sup> analysis of surface and tile water was conducted in 1989, 1990 and 1991. Four treatments, replicated twice, consist of continuous corn planted in 75 cm rows at 67,000 seeds ha<sup>-1</sup> with conventional (moldboard) tillage in the fall with spring disking (CT); continuous corn with ridge tillage, reformed mid-season each year with a Hiniker soil ridger (RT); continuous corn with no-tillage which featured the absence of any cultivation except the planter shoe in the zone of seed placement (NT) and a Kentucky bluegrass treatment (BG). Pioneer 3707 was the corn hybrid used until 1989 however it was unavailable in 1990 and 1991 and Pioneer 3475 was substituted, a variety with a similar heat unit rating. Atrazine (1.8 kg ha<sup>-1</sup>) and metolachlor (2.64 kg ha<sup>-1</sup>) were applied preemergence to control weeds. All plots received 132 kg ha<sup>-1</sup> 8-32-16 at planting. In addition all plots received 168 kg N ha<sup>-1</sup> ammonium nitrate fertilizer metered through a brush applicator when the corn was at the 6 leaf stage. The Kentucky blue grass treatment also received 132 kg ha<sup>-1</sup> of 8-32-16 in the fall. Precipitation was measured at the site with a Belfort rain gauge.

### 1.2.1 Surface and tile water analysis

The plots, 84 m by 12m were centred above a tile drain (0.6m depth) which emptied into an enclosed metal-lined pit. Tile discharge was directed through a Casella proportional logarithmic weir and stage height recorded on a Stevens water level recorder. Manual monitoring of tile flow rate for each event verified the weir calibration. Tile discharge volume was calculated by integration of the area of the hydrograph using Simpsons Rule algorithm.

Surface runoff was determined using a catchment basin installed down-slope (0.5% slope) of the plots. Surface runoff was channelled through a precalibrated 0.23 m H flume. Stage height for each runoff event was recorded on a Belfort water level recorder. Surface discharge volume was estimated by integration of hydrographs.

Tile effluent was collected for analysis of  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{NO}_2^-$ . Surface and tile water samples were manually sampled during each runoff event and stored at 4 °C. The water samples were filtered through 0.45  $\mu\text{m}$  millipore filter. The filtrates were analyzed on a TRAACS 800 autoanalyzer (Bran + Luebbe, Buffalo Grove, IL) for  $\text{NH}_4^+$  using the Berthelot reaction and for  $\text{NO}_3^-$  plus  $\text{NO}_2^-$  using the cadmium reduction method (Tel and Heseltine, 1990). Nitrite concentration was determined without the column and  $\text{NO}_3^-$  content was calculated by difference. Flow weighted concentrations were calculated by taking the sum of the nitrate loss over the year divided by the sum of the total flow volume (Baker and Johnson, 1981).

### 1.2.2 Plant analysis

Two rows of corn (15.2 m) were harvested from each treatment. The cobs were shelled and the grain moisture content was determined with a Dickey-John (Gow Mac III) moisture meter. Grain yield was reported at 15% moisture content. Grain samples were dried at 80 °C, ground with a Wiley mill fitted with a 40 mesh sieve and weighed (0.2 g) into a 75 mL tube and a Kjeldahl digestion performed in a Technicon digestion block. Ammonium sulfate solutions and a blank were similarly digested. The digests were analyzed on a TRAACS 800 autoanalyzer for  $\text{NH}_4^+$  as described previously except that NaOH was added to the EDTA solution to neutralize the excess acid in the digests. Total nitrogen uptake was calculated as the product of grain yield and tissue nitrogen concentration.

## 1.3 RESULTS

### 1.3.1 Surface and tile water analysis

Average yearly rainfall for Eugene Whelan Experimental Station was 819 mm (30 year average). In 1989, rainfall was below average at 709 mm and in 1990 the rainfall was above average at 872 mm. In both 1989 and 1990 rainfall was fairly evenly distributed throughout the year (Fig. 1.1). A drought occurred in 1991 with only 561 mm of rainfall of which 210 mm fell in the growing season. For this reason crop yields were considerably lower than average in 1991.

Surface and tile water samples were collected from each plot from January 29, 1989 to December 31, 1991. In 1989 and 1990 several samples were collected from each plot during each event to ensure that the initial, peak and end of each runoff event was sampled. Although  $\text{NO}_3^-$  content varied between events the variability in  $\text{NO}_3^-$  content within an event was comparatively small. Baker and Johnson (1981) also found that  $\text{NO}_3^-$  concentrations in tile drainage did not change appreciably during a flow event but large changes could occur between flow events. Due to budget constraints in 1991 only one sample was collected and analyzed from each plot for each event.

There were 8 tile runoff events sampled in 1989 (the experiment was started on January 29) and 16 runoff events in 1990. The volume of water which drained through the tiles was greatest between January and March of 1990 (Fig. 1.2). In general more water flowed through the tiles under the CT treatment than under all other treatments. In several events, tile water flow did not occur in all plots (Fig. 1.2). The difference in amount and frequency of tile runoff may have been due to the cumulative effect of the differences in antecedent moisture contents, evapotranspiration (i.e. resulting from differential growth rates of the crop) and hydraulic conductivity (resulting from tillage operations) among treatments. The total volume of water which drained through the tiles was greatest with the CT treatment and least with the BG treatment in both 1989 and 1990 (Fig. 1.3).

There were no apparent differences in tile water loss between the RT and NT treatments.

Nitrate concentration of tile water from all the corn treatments was greater than  $10 \text{ mg N L}^{-1}$  in 79% of all runoff events in contrast to the BG treatment where only 14% of all runoff events had  $\text{NO}_3^-$  concentrations greater than  $10 \text{ mg N L}^{-1}$  (Fig. 1.4). Maximum  $\text{NO}_3^-$  concentration in tile runoff water occurred in July 1989 when there was a runoff event 19-20 days following N application. The conventional tillage plot resulted in  $53.4 \text{ mg N L}^{-1} \text{ NO}_3^-$  in the tile water whereas the RT, NT and BG plots had 37.1, 34.9, and  $2.4 \text{ mg N L}^{-1}$  in the same event. In 1989 the average  $\text{NO}_3^-$  concentration over all runoff events was greatest with the CT treatment ( $17.2 \text{ mg N L}^{-1}$ ) and lowest with the BG treatment ( $1.2 \text{ mg N L}^{-1}$ ) (Fig. 1.5). The average  $\text{NO}_3^-$  concentration for the RT and NT plots was 15.6 and  $14.7 \text{ mg N L}^{-1}$ , respectively. In 1990 all three corn tillage treatments resulted in similar  $\text{NO}_3^-$  concentrations of 13.3, 12.0 and  $11.8 \text{ mg N L}^{-1}$  for the CT, RT and NT treatments with the BG treatment at  $2.6 \text{ mg N L}^{-1}$  (Fig. 1.5).

The total amount of  $\text{NO}_3^-$  lost in each event varied considerably as a result of the combined effect of  $\text{NO}_3^-$  concentration in the tile water and volume of water lost per event (Fig. 1.6). The conventional tillage treatments had the greatest  $\text{NO}_3^-$  loss whereas there was comparatively negligible losses of  $\text{NO}_3^-$  with the bluegrass treatment. There was  $8.6 \text{ kg N ha}^{-1} \text{ NO}_3^-$  lost from the CT plots in the July 1989 runoff event, about half of this amount lost from the RT and NT treatments, and only  $0.4 \text{ kg N ha}^{-1}$  lost from the BG treatment. Although there were no runoff events in 1990 which resulted in  $\text{NO}_3^-$  losses as great as those which occurred July 1989, more  $\text{NO}_3^-$  was lost through tiles in 1990 due to the greater number of runoff events in that year. In 1989 there was  $18 \text{ kg N ha}^{-1}$  lost through tile runoff from the CT treatment,  $14 \text{ kg N ha}^{-1}$  lost from both the RT and NT treatments and  $1 \text{ kg N ha}^{-1}$  lost from the BG treatment (Fig. 1.7). In 1990 the  $\text{NO}_3^-$  losses were even greater as a result of more rainfall with  $29 \text{ kg N ha}^{-1}$  lost from the CT treatment,  $20 \text{ kg N ha}^{-1}$  lost from both the RT and NT treatments and  $3 \text{ kg N ha}^{-1}$  lost from the BG treatment. The average  $\text{NO}_3^-$  losses

from the corn tillage treatments in 1989 and 1990 represented between 9 to 13% of the N fertilizer added.

Results from 1991 are reported separately as a result of the drought. Further, tile water flow data were not obtained for the ridge tillage treatment due to instrumentation problems. The concentration of  $\text{NO}_3^-$  in tile water was greater with all treatments in 1991 as compared to 1989 and 1990 as a result of the poor corn growth and low N uptake in this dry year. There was  $0.22 (\pm 0.07)$ ,  $0.41 (\pm 0.03)$  and  $0.02 (\pm <0.01)$  ML  $\text{ha}^{-1}$  of tile runoff from the CT, NT and BG treatments, respectively. The flow-weighted  $\text{NO}_3^-$  concentration in tile water for 1991 from the CT and NT treatments was  $26.4$  and  $28.5$  mg N  $\text{L}^{-1}$ , respectively whereas under the BG treatment the flow-weighted concentration was  $14$  mg N  $\text{L}^{-1}$ . Only  $7.4 (\pm 4.2)$ ,  $11.1 (\pm 2.0)$  and  $0.3 (\pm 0.2)$  kg N  $\text{ha}^{-1}$  was lost from the CT, NT and BG treatments in 1991 as a result of the low volume of tile runoff. Ammonium leaching in tile water was very low with less than  $0.3$  kg N  $\text{ha}^{-1}$  lost from all treatments in 1989, 1990 and 1991 (data not presented).

The volume of water which drained through the tiles of the corn tillage systems always exceeded the volume of surface runoff, typically by factors of 2 to 4. The ridge tillage treatment resulted in the greatest volume of surface runoff in all years (1989-1991) and the BG treatment the least (Table 1.1). Average  $\text{NO}_3^-$  concentrations in surface runoff were greater for the corn tillage treatments than the BG treatment. Differences between tillage treatments were however very small with an average of  $7.6$  mg N  $\text{L}^{-1}$  in 1989 and  $5.2$  mg N  $\text{L}^{-1}$  in 1990 for the corn tillage systems.

Nitrate losses through surface runoff were also considerably less than tile runoff in 1989 and 1990 as both the volume of water lost through surface runoff events and the concentration of  $\text{NO}_3^-$  in the surface runoff was considerably lower. In 1989 there was less than  $3$  kg N  $\text{ha}^{-1}$  lost in surface runoff across treatments, with the ridge tillage treatment having the greatest loss and the BG treatment the least. In 1990 with a greater amount of rainfall and volume of water lost through

surface runoff, the  $\text{NO}_3^-$  losses ranged from 0.1 kg N ha<sup>-1</sup> for the BG treatment to 5.5 kg N ha<sup>-1</sup> with the RT treatment. Although there were high  $\text{NO}_3^-$  concentrations in the surface runoff for the RT and NT treatments in 1991, the low volume of surface runoff resulted in less than 2 kg N ha<sup>-1</sup> total  $\text{NO}_3^-$  losses.

### 1.3.2 Plant analysis

The conventional tilled corn treatments had the lowest grain yields in both 1989 and 1990 and the conservation tillage treatments had greater yields (Table 1.2). The no-tillage treatment produced higher grain yields than the ridge tilled treatment in 1989 but the reverse occurred in 1990. In 1991 the drought restricted corn growth severely. Although higher corn yields were obtained with the conventional tillage treatment than the conservation tillage treatments in 1991, the corn growth was severely stunted for all treatments.

The nitrogen uptake values paralleled the yield results in that more N was contained in the conservation tillage treatments than the conventional tillage treatment in both 1989 and 1990. Since a total of 178.6 kg N ha<sup>-1</sup> was applied to all corn treatments (10.6 kg N ha<sup>-1</sup> at planting and 168 kg N ha<sup>-1</sup> with a side-dressed application) the uptake values ranged from 35 to 40% in 1989, from 41 to 51% in 1990 and only 7 to 14% in 1991. This nitrogen was removed from the site with the grain and was therefore not available for leaching.

## 1.4 DISCUSSION

The primary loss of nitrogen from the corn production system was through tile runoff. The levels of  $\text{NO}_3^-$  were well above the acceptable limit of 10 mg N L<sup>-1</sup> for all corn production systems. Conservation tillage did reduce these losses somewhat as there were lower volumes of water lost in tile runoff and lower concentrations of  $\text{NO}_3^-$  in tile runoff. Bolton et al. (1970) in an earlier study

with a Brookston clay loam found that the volume of water which flowed through soil was the predominant factor responsible for N loss. Bergstrom (1987) also reported that yearly  $\text{NO}_3^-$  fluxes reflected runoff volumes since the concentration of  $\text{NO}_3^-$  was fairly stable for each particular cropping system investigated. Further the increased yield and N-uptake in grain resulting from the conservation tillage systems reduced the amount of  $\text{NO}_3^-$  available for leaching. Even though conservation tillage systems improved yields and N uptake and lowered leaching losses, the concentration of  $\text{NO}_3^-$  in the runoff water was still above the  $10 \text{ mg N L}^{-1}$  limit. It is interesting to note that the increase in N uptake in conservation tillage systems over the conventional tillage was similar to the reduction in  $\text{NO}_3^-$  leaching losses.

The bluegrass sod had the lowest losses of  $\text{NO}_3^-$  in both surface and tile water and the  $\text{NO}_3^-$  concentration in these waters was usually below  $10 \text{ mg N L}^{-1}$ . Bolton et al. (1970) also found that the continuous corn with fall plowing resulted in the greatest losses of N and the continuous bluegrass sod the least. The results from this study demonstrated that the concentration of  $\text{NO}_3^-$  in tile water was considerably higher after a drought which resulted in decreased yields and N uptake. Hubbard et al. (1984) also found that  $\text{NO}_3^-$  concentration in tile runoff after an extensive drought was much greater than in average rainfall years. Lower corn yields and crop uptake can result in increased  $\text{NO}_3^-$  concentrations in tile drainage (Kladivko et al., 1991).

Blevins et al. (1990) reported that surface runoff volume was greater under conventional tillage than under either a chisel plow or no-tillage system. In contrast, in this study, the volume of water lost in surface runoff was greater with the reduced tillage systems than with the conventional tilled treatment in 1989 and 1990. The Brookston soil used in this study exhibited shrinking and swelling characteristics. The cracks which formed on the soil surface were observed to be greater with the conventional tillage treatment than the conservation tillage treatments. Therefore the conventional tillage treatment probably had more water lost through preferential flow which would

increase the relative amount of tile runoff and decrease the relative amount of surface runoff. Further, greater amounts of runoff could occur in spring with a no-tillage system which has a smooth soil surface resulting from a lack of cultivation compared to a conventional tilled system which can have a rough surface resulting from recent cultivation (Angle et al., 1984).

Ammonium loss in either surface or tile runoff was found to be very low for all treatments in all years in this study. Kladrivko et al. (1991) also found that the annual  $\text{NH}_4^+$  loss in subsurface drainage was very low ( $0.5 \text{ kg N ha}^{-1}$ ) for an intensive corn production system receiving  $285 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ . Ammonium concentrations in runoff water under corn production systems were also found to be less than  $0.1 \text{ mg N L}^{-1}$  from lysimeters (Prunty and Montgomery, 1991).

Although ridge tillage and no-tillage corn production systems decreased the concentration of  $\text{NO}_3^-$  in tile runoff and total nitrogen losses, these concentrations were still above the  $10 \text{ mg N L}^{-1}$  limit. Additional best management practices would have to be implemented in order to reduce the concentration of  $\text{NO}_3^-$  in tile water even further.

## 1.5 ACKNOWLEDGEMENTS

We are grateful to P.S. Hencher and N. Taylor for their capable technical assistance. We also wish to extend acknowledgements to the Soil and Environmental Enhancement Program (SWEEP) for financial support.

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Table 1.1 Volume of water, nitrate and ammonium loss in surface runoff.

| Treatment | Year | Volume              | NH <sub>4</sub> <sup>+</sup> Loss | NO <sub>3</sub> <sup>-</sup> Concentration | NO <sub>3</sub> <sup>-</sup> Loss |
|-----------|------|---------------------|-----------------------------------|--------------------------------------------|-----------------------------------|
|           |      | kL ha <sup>-1</sup> | kg N ha <sup>-1</sup>             | mg N L <sup>-1</sup>                       | kg N ha <sup>-1</sup>             |
| CT        | 1989 | 265 (31)*           | 0.04 (0.02)                       | 7.05 (2.03)                                | 1.87 (0.31)                       |
|           | 1990 | 620 (107)           | 0.01 (<0.01)                      | 4.04 (0.76)                                | 2.51 (0.01)                       |
|           | 1991 | 86 (18)             | <0.01 (<0.01)                     | 3.43 (1.86)                                | 0.29 (0.21)                       |
| RT        | 1989 | 382 (52)            | 0.10 (0.03)                       | 6.86 (0.62)                                | 2.62 (0.58)                       |
|           | 1990 | 904 (61)            | 0.44 (0.31)                       | 6.06 (0.50)                                | 5.48 (0.82)                       |
|           | 1991 | 136 (73)            | 0.01 (0.01)                       | 12.4 (3.6)                                 | 1.70 (1.12)                       |
| NT        | 1989 | 298 (29)            | 0.17 (<0.01)                      | 8.86 (2.08)                                | 2.64 (0.80)                       |
|           | 1990 | 737 (29)            | 0.01 (<0.01)                      | 5.56 (0.94)                                | 4.10 (0.85)                       |
|           | 1991 | 74 (11)             | 0.06 (0.04)                       | 26.7 (22.2)                                | 1.99 (1.30)                       |
| BG        | 1989 | 37 (9)              | 0.05 (0.04)                       | 8.59 (3.85)                                | 0.32 (0.20)                       |
|           | 1990 | 173 (1)             | 0.02 (0.01)                       | 0.42 (0.11)                                | 0.08 (0.02)                       |
|           | 1991 | 8 (6)               | <0.01 (<0.01)                     | 0.98 (**)                                  | 0.01 (0.01)                       |

\* All numbers in parentheses are standard errors (n=2).

\*\* Nitrate concentration was only determined in one replicate as a result of insufficient water flow in the second replicate.

Table 1.2 Corn grain yield and N uptake for conventional, ridge-tillage and no-tillage treatments.

| Treatment   | Grain Yield        | N uptake              |
|-------------|--------------------|-----------------------|
|             | t ha <sup>-1</sup> | kg N ha <sup>-1</sup> |
| <u>1989</u> |                    |                       |
| CT          | 5.71 (0.33)*       | 61.7 (2.4)            |
| RT          | 6.01 (0.57)        | 64.9 (5.7)            |
| NT          | 6.42 (0.73)        | 72.4 (8.7)            |
| <u>1990</u> |                    |                       |
| CT          | 7.57 (0.31)        | 73.0 (3.6)            |
| RT          | 9.07 (0.17)        | 90.4 (2.3)            |
| NT          | 8.51 (0.08)        | 82.9 (1.0)            |
| <u>1991</u> |                    |                       |
| CT          | 1.91 (0.07)        | 25.4 (1.5)            |
| RT          | 1.06 (0.18)        | 15.2 (4.9)            |
| NT          | 0.88 (0.11)        | 12.5 (2.8)            |

\* All numbers in parentheses are standard errors (n=2).

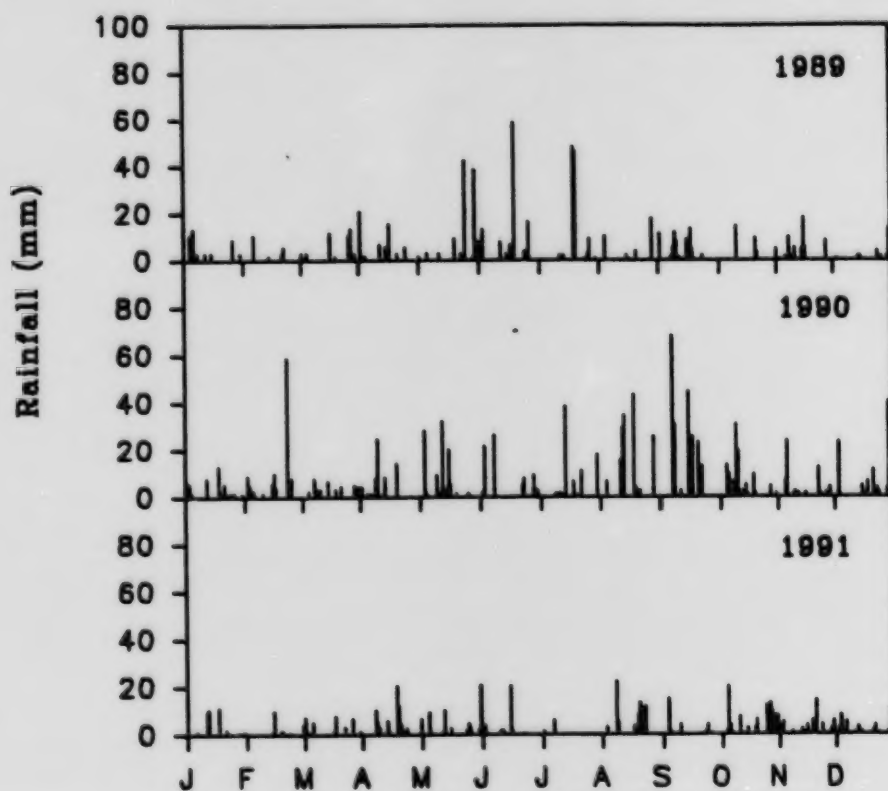


Figure 1.1 Daily precipitation from January 1, 1989 till December 31, 1991 at the Woodslee experimental site.

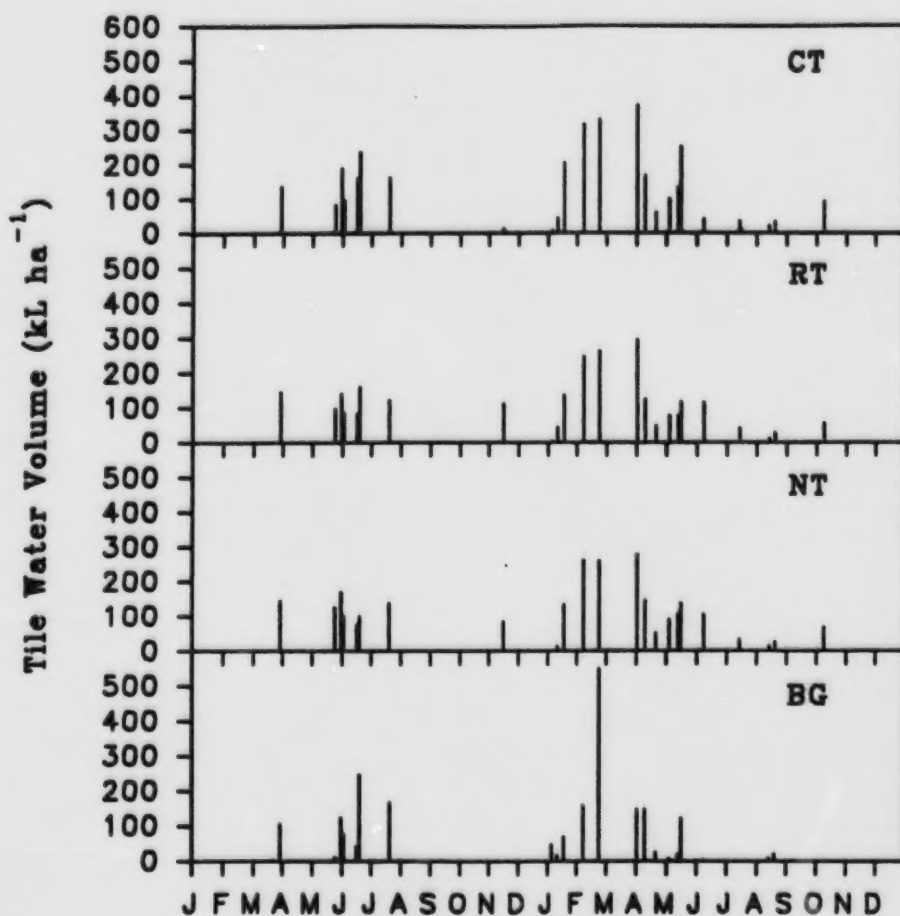


Figure 1.2 Tile water losses for each runoff event from January 29, 1989 till December 31, 1990 for the conventional tillage (CT), ridge tillage (RT), no-tillage (NT) and Kentucky bluegrass (BG) treatments.

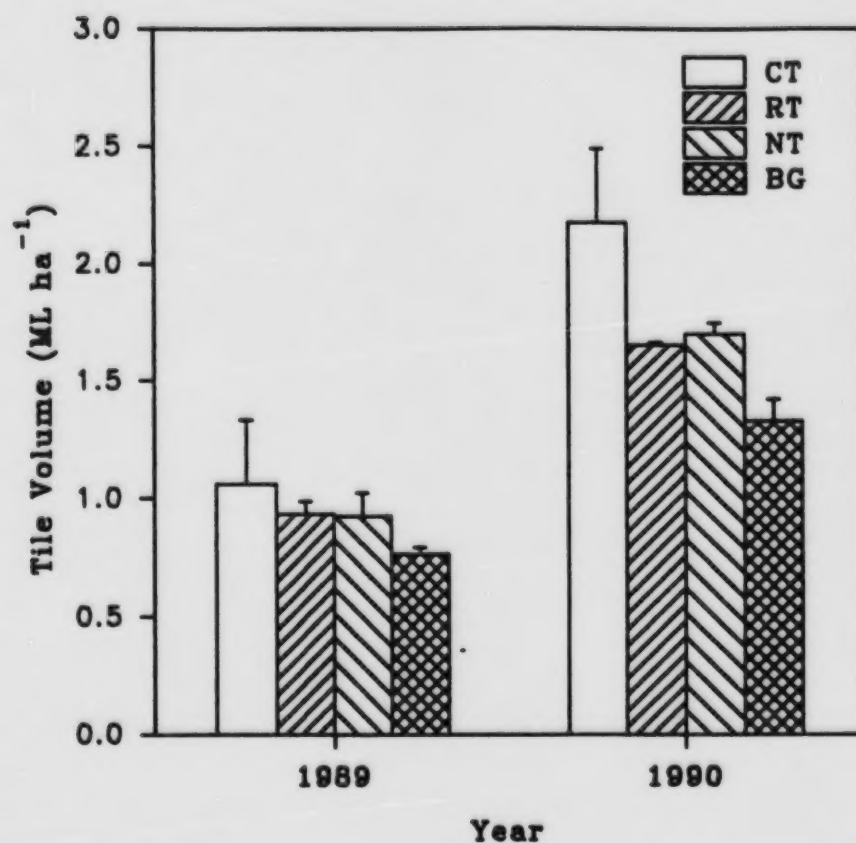


Figure 1.3 Cumulative tile water losses for the conventional tillage (CT), ridge tillage (RT), no-tillage (NT) and Kentucky bluegrass (BG) treatments in 1989 (January 29 - December 31) and 1990 (January 1 - December 31).

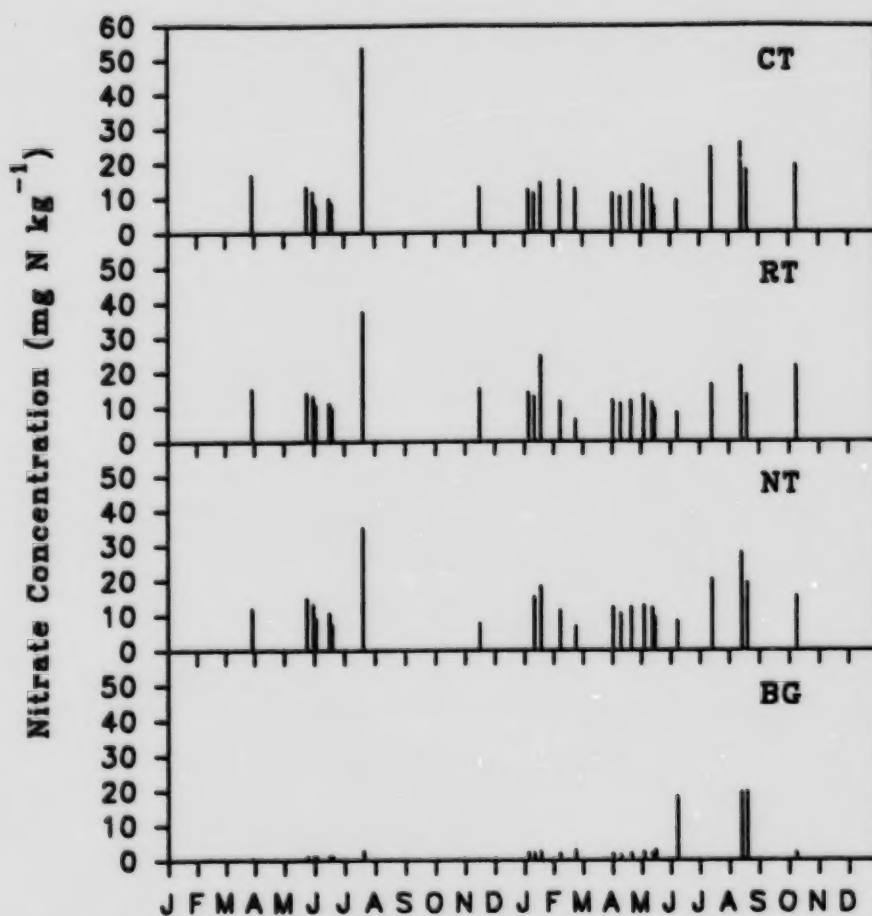


Figure 1.4 Nitrate concentration in tile runoff for each event from January 29, 1989 till December 31, 1990 for the conventional tillage (CT), ridge tillage (RT), no-tillage (NT) and Kentucky bluegrass (BG) treatments.

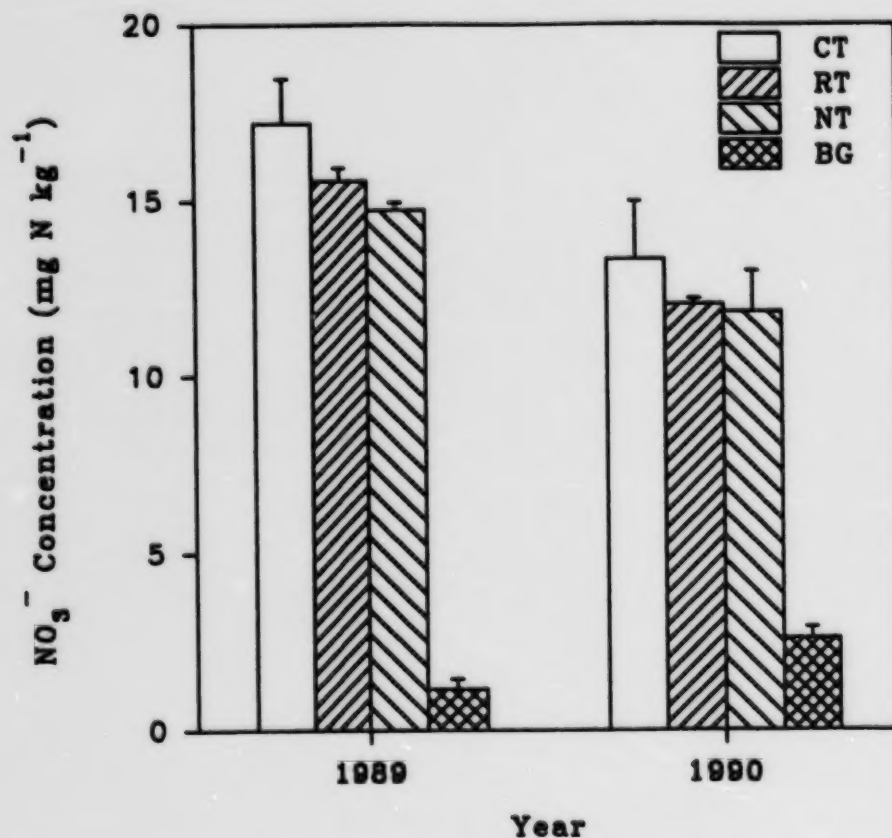


Figure 1.5 Flow-weighted mean  $\text{NO}_3^-$  concentration in tile water for the conventional tillage (CT), ridge tillage (RT), no-tillage (NT) and Kentucky bluegrass (BG) treatments in 1989 (January 29 - December 31) and 1990 (January 1 - December 31).

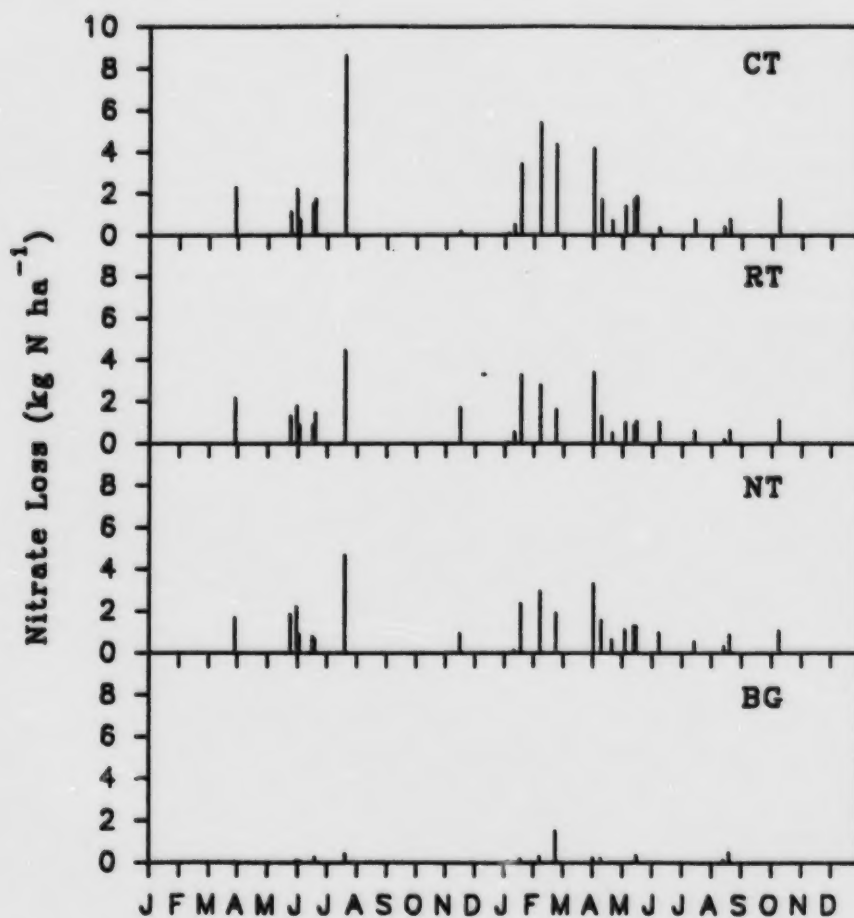


Figure 1.6 Nitrate loss in tile runoff for each event from January 29, 1989 till December 31, 1990 for the conventional tillage (CT), ridge tillage (RT), no-tillage (NT) and Kentucky bluegrass (BG) treatments.

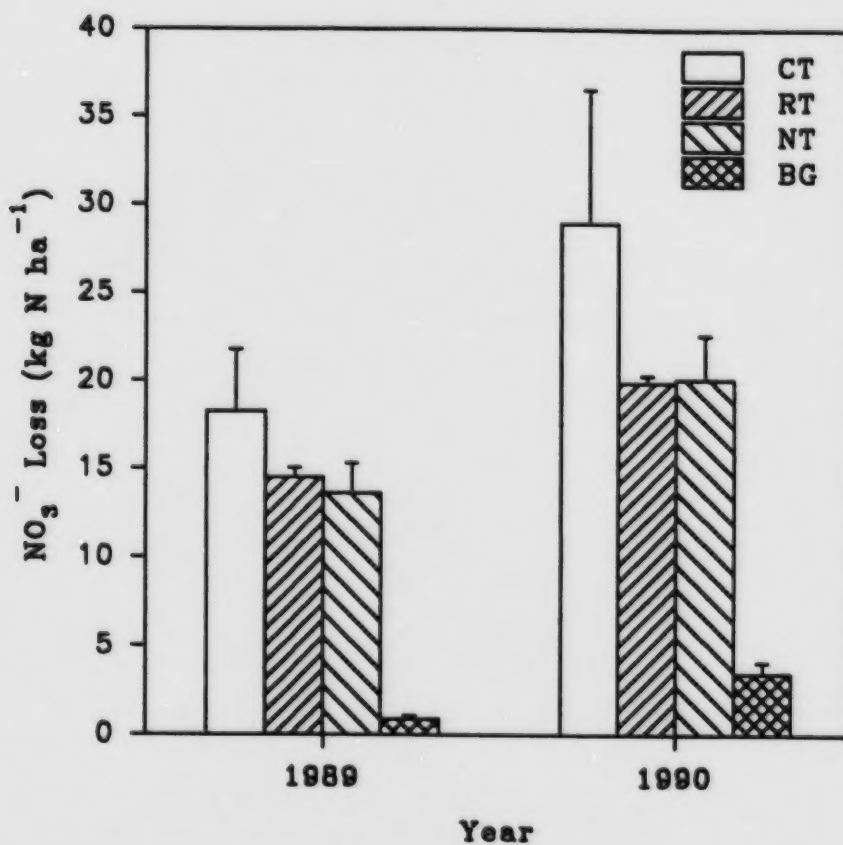


Figure 1.7 Cumulative  $\text{NO}_3^-$  loss in tile runoff for the conventional tillage (CT), ridge tillage (RT), no-tillage (NT) and Kentucky bluegrass (BG) treatments in 1989 (January 29, - December 31) and 1990 (January 1 - December 31).



## 2 BACKGROUND AND POTENTIAL DENITRIFICATION VARIATION WITH DEPTH UNDER CONSERVATION AND CONVENTIONAL TILLAGE

### 2.1 INTRODUCTION

Conservation tillage is a rapidly increasing soil management method since it is considered to be a relatively economical means of reducing soil erosion while increasing water infiltration and storage (Dick *et al.*, 1989). However, minimum or no-tillage is expected to influence soil physical and biological processes including, for example, those relating to N-utilization, conversion and transport. Relatively few studies have dealt with identification of possible correlations between tillage practice and denitrification (Staley *et al.* 1990), although denitrification (along with nitrification) is a substantial source of the important atmospheric trace gases, NO, NO<sub>2</sub> (NO<sub>x</sub>) and N<sub>2</sub>O and may account for losses ranging between 1 and 52% of added fertilizer N (Mosier *et al.*, Smith *et al.*, 1988; Ryden and Lund, 1980). Staley *et al.*, 1990, found most potential denitrification and nitrification activity appeared in the surface (0-3.8 cm) layer under no till (NT) treatment. They reported correlations with tillage, season and location for potential denitrification activity. Only location (with row versus between rows) effects were observed for potential nitrification activity. In agreement with other workers (Rice and Smith, 1982; Groffman *et al.*, 1987; Parkin *et al.* 1987) they suggested that losses of N under NT should be greater than under conventional till (CT).

Losses of N- species dissolved in water that drains from or runs off land can also be significant. Most measurements have focused on NO<sub>3</sub><sup>-</sup>. For example Schepers *et al.*, 1991 observed a correlation between groundwater NO<sub>3</sub><sup>-</sup> and residual N in surface 0.9 m soil prior to the growing season. Several reports have shown that gaseous denitrification products lost from soil by leaching can be similar to amounts of those lost in gaseous emission from surfaces (Dowdell *et al.*, 1979; Bowden and Borman, 1987). On the other hand dissimilatory nitrate reduction and denitrification

activity in the soil through which the water effuses decrease  $\text{NO}_3^-$ ,  $\text{NO}_2^-$  and C concentrations and hence can be viewed as beneficial processes since they can mitigate contamination of natural water systems by these species (Smith and Duff, 1988).

In this paper we report measurements of background and potential denitrification rates at depths from the surface to 0.9 m in order to identify possible effects of several tillage methods may have on the denitrification process.

## **2.2 MATERIALS AND METHODS**

### **2.2.1 Plot Description**

The tillage/crop plots were established in 1983 at Eugene Whelan substation of Agriculture Canada (Harrow). Four treatments, replicated twice, consist of continuous corn (Pioneer 3707) with conventional (mouldboard) tillage (CT) in the fall with spring disking; continuous corn with ridge tillage (RT) which were reformed mid-season each year, continuous corn with no tillage (NT) and a Kentucky bluegrass plot (BG). The plots were 84m by 12m and were centred above a tile drain. All plots received  $132 \text{ kg ha}^{-1}$  8-32-16 at planting. In addition all plots received  $168 \text{ kg N ha}^{-1}$  ammonium nitrate fertilizer when the corn was at the 6 leaf stage. The Kentucky bluegrass plot also received  $132 \text{ kg ha}^{-1}$  of 8-32-16 in the fall. Atrazine ( $1.8 \text{ kg ha}^{-1}$ ) and metolachlor (Dual) were applied preemergence to control weeds.

### **2.2.2 Background nitric oxide and nitrous oxide production from the crop/tillage treatments using the continuous flow column technique**

Soil cores (30 cm) were taken in October 1989 and July 1990 with a JMC zero contamination tube and backsaver handle (Clements Associates Inc., Newton, Iowa, USA). The intact cores with acetate liner were weighed and then placed in thermostatted ( $20 \pm 0.1^\circ\text{C}$ ) columns which formed part

of a gas flow-through system similar to that previously described (McKenney *et al.*, 1982). Humidified  $N_2$  gas was flowed through the soil at  $395 \text{ cm}^3 \text{ min}^{-1}$ . Net production rates of NO and  $N_2O$  evolved from these soil columns were measured at 0.25, 2, 5, 9, and 24 h. Rates were calculated from the equation:

$$\text{net NO production rate} = \frac{[NO]f_c}{m}$$

where:  $f_c$  is the total flow rate ( $\text{mL min}^{-1}$ ) through the column and  $m$  is the oven-dry mass (kg) of soil.

A similar expression was used for  $N_2O$  rates. Nitric oxide was analyzed with a chemiluminescent NO/ $NO_2$ / $NO_x$  analyzer and 1 mL gas samples were analyzed for  $N_2O$  using a Porapak Q column on a Hewlett Packard gas chromatograph fitted with an electron capture detector. After 24 h, moist soil samples (15 g) were removed from the columns and extracted with 100 mL of 2M KCl. The extracts were subsequently analyzed with a TRAACS 800 autoanalyzer for  $NH_4^+$ ,  $NO_3^-$  plus  $NO_2^-$  and  $NO_2^-$  as described previously (Drury *et al.*, 1991). Water content was determined gravimetrically.

### 2.2.3 Potential denitrification estimates of the crop/tillage treatments using the acetylene inhibition technique

Soil cores (30 cm) were taken in October 1990 with a JMC zero contamination tube and backsaver handle (Clements Associates Inc., Newton, Iowa, USA). The soil was removed from the cores and separated into 5 cm increments. Soil from three cores were composited. Soil (15 g oven dry basis,  $105^\circ\text{C}$ ) samples from the crop/tillage treatments were weighed into 250 mL Erlenmeyer flasks which were fitted with suba-seals through which flushing with helium,  $C_2H_2$  addition, and sampling of the evolved gases could be accomplished. Nitrate ( $100 \text{ mg N kg}^{-1}$ ) solutions were added to each flask. Distilled water was added to bring the soils to -33 kPa water potential adjusted for the

quantity of water contained in the nitrate solutions. A multi-port vacuum manifold allowed five flasks to be simultaneously flushed with helium. The flasks were equilibrated with helium at 1 atmosphere pressure. A 25 mL (10% of the gas volume) headspace gas sample was removed from each flask with a syringe and acetylene (25 mL) was then injected into each flask to inhibit nitrous oxide reduction (Yoshinari *et al.*, 1977). The flasks were incubated at 20°C and gas samples (0.25 mL or 1.0 mL) were removed after 3 d. Samples were analyzed for N<sub>2</sub>O using a gas chromatograph equipped with a <sup>63</sup>Ni electron capture detector fitted with a Porapak Q column. The N<sub>2</sub>O concentration was adjusted to take account of dissolved N<sub>2</sub>O using the Bunsen absorption coefficient (Tiedje, 1982). Carbon dioxide was analyzed using a Porapak N column and a thermal conductivity detector.

After 3 d, the soils were extracted with 100 mL 2M KCl and subsequently analyzed for NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup> plus NO<sub>2</sub><sup>-</sup>, and NO<sub>2</sub><sup>-</sup> alone as described previously. Nitrate content was calculated by difference between analyses.

#### 2.2.4 Dinitrogen production using the gas flow-through technique with C<sub>2</sub>H<sub>2</sub> addition

Some experiments were carried out in an effort to measure background N<sub>2</sub> production using the continuous flow column technique. Direct precise measurement of N<sub>2</sub> is difficult mainly because of its very large ambient concentration. In the flow system the problem is even greater since N<sub>2</sub> is the terminal product in the denitrification process and is expected to be at lower concentrations than NO and N<sub>2</sub>O (McKenney *et al.*, 1982). Consequently instead of directly measuring N<sub>2</sub> we employed the C<sub>2</sub>H<sub>2</sub> inhibition technique and looked for an increase in N<sub>2</sub>O production following C<sub>2</sub>H<sub>2</sub> addition. A constant flow (40 mL min<sup>-1</sup>) of C<sub>2</sub>H<sub>2</sub> was added to the carrier gas providing a constant total flow of 395 mL min<sup>-1</sup> to the soil columns. The effluent gas was sampled for N<sub>2</sub>O (1 mL) by gas chromatography.

## 2.3 RESULTS

### 2.3.1 Nitric oxide and nitrous oxide production from the crop/tillage treatments using the continuous flow column technique

October 1989

Nitric oxide production data were determined at three depths, 0-30, 30-60 and 60-90 cm (Fig. 2.1). These "background" rates were generally low with highest rates observed in the surface 0-30 cm depth. A rapid decrease in NO production was observed under all treatments with rates being less than  $25 \mu\text{g N kg}^{-1}\text{d}^{-1}$  between 30-90 cm. In the surface 0-30 cm depth, CT corn showed marginally highest, and RT corn the lowest rates. Background  $\text{N}_2\text{O}$  production also decreased with depth but more  $\text{N}_2\text{O}$  was produced at 60-90 cm than the 30-60 cm depth for all treatments (Fig 2.2). The sum,  $\text{NO} + \text{N}_2\text{O}$  production provides a measure of background denitrification rates in these soils (Fig. 2.3). In our gas flow-through system rapid removal of NO and  $\text{N}_2\text{O}$  by the high flow rate of carrier gas minimizes production of  $\text{N}_2$  (McKenney *et al.*, 1982). The highest background denitrification rates occurred at the 0-30 cm depth with CT showing the greatest and RT the lowest rates. Slightly greater denitrification rates are evident at the 60-90 cm than the 30-60 cm depth. The average moisture content was  $22.3 \pm 5.6\%$  ( $n=48$ ).

July 1990

Nitric oxide production at three depths, 0-30, 30-60 and 60-90 cm, was determined in intact (unamended) cores (Fig. 2.4). Production rates decreased with increasing depth although not as rapidly as observed in 1989. In this study NO production ranged between 210 to  $360 \mu\text{g N kg}^{-1}\text{d}^{-1}$  in the 0-30 cm depth which was similar to the range of 130 to  $320 \mu\text{g N kg}^{-1}\text{d}^{-1}$  obtained in July 1989 samples. Nitric oxide production from NT and RT samples were greater than the CT samples. Sample to sample variability was very high, indicative of the very large spatial variability in this soil (McKenney *et al.*, 1980).

In the 1989 samples NO production rates decreased to values less than  $25 \mu\text{g N kg}^{-1} \text{d}^{-1}$  between 30 and 90 cm depths whereas in the 1990 samples NO production remained greater than  $44 \mu\text{g N kg}^{-1} \text{d}^{-1}$ . The earlier data showed slightly higher rates under CT and lowest rates under RT. In 1990 NT and RT were highest and CT lowest in the 0-30 cm depth. At the 30-60 cm and 60-90 cm depths NO production remained high, 225 and  $190 \mu\text{g N kg}^{-1} \text{d}^{-1}$  respectively under BG.

Background  $\text{N}_2\text{O}$  production rates decreased with depth in much the same way as NO production (Fig. 2.5). Rates ranged from  $34 \mu\text{g N kg}^{-1} \text{d}^{-1}$  from the CT sample taken at 60-90 cm depth to  $471 \mu\text{g N kg}^{-1} \text{d}^{-1}$  from the NT plot sampled at 0-30 cm depth. In 1990 lowest rates were generally observed at the 60-90 cm depth in contrast to the 1989 study where rates at the 60-90 cm depth were slightly higher than at the 30-60 cm depth. Nitrous oxide production from NT were highest and CT lowest in samples from the 0-30 cm depths similar to NO production. The sum  $\text{NO} + \text{N}_2\text{O}$  production, shown in Fig. 2.6, is a measure of background denitrification rates. It is evident that although rates are substantially higher near the surface, the rates remain relatively high at depths down to 90 cm. The average moisture content was  $22.3 \pm 3.9\%$  ( $n=14$ ).

### 2.3.2 Potential denitrification estimates of the crop/tillage treatments using the acetylene inhibition technique

Maximum potential denitrification enzyme activity is usually measured on soils amended with  $\text{NO}_3^-$ , glucose and chloramphenicol (Smith and Tiedje, 1979) so that  $\text{NO}_3^-$  or C is not limiting. In this study the available C supply under the varying tillage systems was examined by adding only  $\text{NO}_3^-$  to the soils. Without C addition differences in measured denitrification activity reflect differences in C content and/or denitrifier population which depends on adequate available C, in the soil under the various tillage treatments. Hence the possible advantage of one tillage system over another for ameliorating  $\text{NO}_3^-$  leaching into groundwater would be indicated by a relatively large denitrification potential with excess  $\text{NO}_3^-$  added.

Denitrification potential as measured by  $N_2O$  production (Fig. 2.7) was much greater in the surface 0-5 cm increment for all treatments except CT corn. Most  $N_2O$  production occurred in the NT bluegrass plot followed by NT corn, then RT corn and finally CT corn. Nitrous oxide production from samples taken between the corn rows was similar (Fig. 2.8). The amount of  $N_2O$  produced decreased dramatically with depth for all treatments except for CT corn.

Carbon dioxide production reflecting overall microbial activity, (Figs. 2.9 and 2.10) for the tillage treatments at the various depths followed the same pattern as that of the  $N_2O$  production. The NT bluegrass produced the greatest amount ( $> 100 \text{ mg C kg}^{-1}$ ) in the 0-5 cm increment. More  $CO_2$  was produced between the corn rows in the CT corn samples.

Nitrate concentrations inversely reflected the  $N_2O$  pattern (Figs. 2.11 and 2.12). Most  $NO_3^-$  was lost in the upper 0-5 cm depth in the NT bluegrass samples. Very little, if any, change in  $NO_3^-$  concentration was evident in the CT corn samples with increasing depth.

Nitrite levels shown in Figures 2.13 and 2.14, were relatively low ( $< 8 \text{ mg N kg}^{-1}$ ) and generally followed the  $N_2O$  and  $CO_2$  pattern with depth. The results for  $NO_2^-$  however were somewhat more scattered.

Ammonium levels (Figs. 2.15 and 2.16) ranged up to  $\sim 12 \text{ mg N kg}^{-1}$  in the NT bluegrass 0-5 cm increment samples. Once again, the pattern conformed to that shown by the  $N_2O$  and  $CO_2$  variation with depth. With the exception of CT corn, all other treatments showed a rapid decrease in  $NH_4^+$  concentrations with increasing depth.

### 2.3.3 Dinitrogen production using the gas flow-through technique with $C_2H_2$ addition

Preliminary results showed insignificant increases in  $N_2O$  production following  $C_2H_2$  additions to carrier gas flowing through soil columns. This implies that  $N_2$  formation in the absence of  $C_2H_2$  was also insignificant in these experiments. Although these results are preliminary, and we anticipate

further experiments in the near future, the data obtained so far support our contention that rapid sparging of NO and N<sub>2</sub>O products from the soil columns prevents formation of large quantities of N<sub>2</sub> under the moisture and temperature conditions normally employed.

## 2.4 DISCUSSION

Background denitrification rates were approximately the same magnitudes in 1990 as in 1989, and decreased with depth under all tillage systems. Apparently no relationship between tillage system and production rates exists from one year to another. Relatively large variations in rates persist within and among sampling sites.

Denitrification was found to occur in a clay loam soil down to 0.9 m depth in all crop/tillage treatments. Although carbon and nitrate levels limited denitrifier activity and the microbial biomass level at depths below 30 cm, it appears that both species were present in sufficient quantities for NO and N<sub>2</sub>O to be produced. Comparisons of background denitrification rates, NO and N<sub>2</sub>O production rates (Figs. 2.3 and 2.6) with potential denitrification, N<sub>2</sub>O production with excess NO<sub>3</sub><sup>-</sup> added, (Fig. 2.7) shows that unamended soil underlying the bluegrass and NT treatments (0-30 cm depth) are more NO<sub>3</sub><sup>-</sup> limited than the corresponding CT and RT plots. Potential production following NO<sub>3</sub><sup>-</sup> addition was much greater in Kentucky bluegrass and RT treatments. Background rates were relatively low compared to potential rates with excess NO<sub>3</sub><sup>-</sup> added. For example a NO + N<sub>2</sub>O background rate of ~800 µg N kg<sup>-1</sup> d<sup>-1</sup> (Fig. 2.6) for RT corn would correspond to a production of only 2.4 µg N kg<sup>-1</sup> in 3 days compared to potential N<sub>2</sub>O production of 20 µg N kg<sup>-1</sup> (Fig. 2.7) for the 0 to 30 cm depth for the same tillage method. For bluegrass the difference was even greater. When nitrate was added, the bluegrass treatment had the highest denitrification rate probably due to the increased carbon supply from root exudation and decay. Conventional till and NT had the lowest potential N<sub>2</sub>O production. However, most of the added NO<sub>3</sub><sup>-</sup> was not denitrified after 3 d and since

microbial biomass levels were roughly similar in all treatments, these results suggest that soluble carbon was limiting in all treatments, especially continuous corn. In a recent study, carbon was found to be the limiting factor for denitrification in southwestern Ontario soils (Drury *et al.*, 1991).

The lower potential denitrification rate with the conventional tillage treatment in the top 0-5 cm depth was probably the result of tillage diluting the soluble carbon from the top 0-5 cm and increasing the soluble carbon in the 5-10 cm depth. In the reduced tillage treatments, there was a greater demarcation in denitrification activity between the 0-5 cm depth and the lower depths than with the CT treatment. In addition, tillage aerated the CT treatment which would have accelerated organic carbon decomposition by the aerobes. This would limit the amount of soluble carbon available for denitrification especially by the end of the growing season (October).

Carbon dioxide production showed that microbial activity decreased rapidly with depth following approximately the same pattern as  $N_2O$  production. Nitrite is the primary intermediate in the denitrification process and, not surprisingly, highest concentrations were generally in the upper 0-5 cm increment. Nitrate levels were lowest where denitrification was greatest. At all depths except the 0-5 cm layer,  $NO_3^-$  levels were quite uniform at  $\sim 100 \text{ mg N kg}^{-1}$  indicating similar low denitrification activity in all treatments. The  $NH_4^+$  concentrations which again followed a similar pattern of change with depth as the denitrification potential may indicate corresponding changes in dissimilatory nitrate reduction.

Our observation that both background and potential denitrification decreased with depth down to 0.9 m, was similar to observations made by others (Parkin and Meisinger (1989); Khan and Moore (1968); Cho *et al.*, (1979)). In this study the low denitrification potential and low  $CO_2$  production at depth below the top 5 cm suggests relatively low denitrifier population at lower depths under all tillage treatments. Hence in these plots denitrification would not be expected to greatly ameliorate  $NO_3^-$  loss by leaching. A similar conclusion was made by Parkin and Meisinger, (1989).

In their study, carried out in Maryland U.S.A., the soil was well-drained and underlaid by sand. The Brookston soil in this study was poorly drained.

The agronomic implications of these results is that denitrification would be reduced in the conservation tillage systems if nitrogen was added or leached below the 5 cm zone. This is especially true for the reduced tillage system as the gulleys between the ridges are wetter and the combination of anaerobic conditions with soluble carbon and nitrate would be conducive to denitrification losses.

## 2.5 ACKNOWLEDGEMENTS

We are grateful to P.S. Hencher, S. Medica and N. Taylor for their capable technical assistance. We also wish to extend acknowledgements to the Soil and Environmental Enhancement Program (SWEEP) for financial support.

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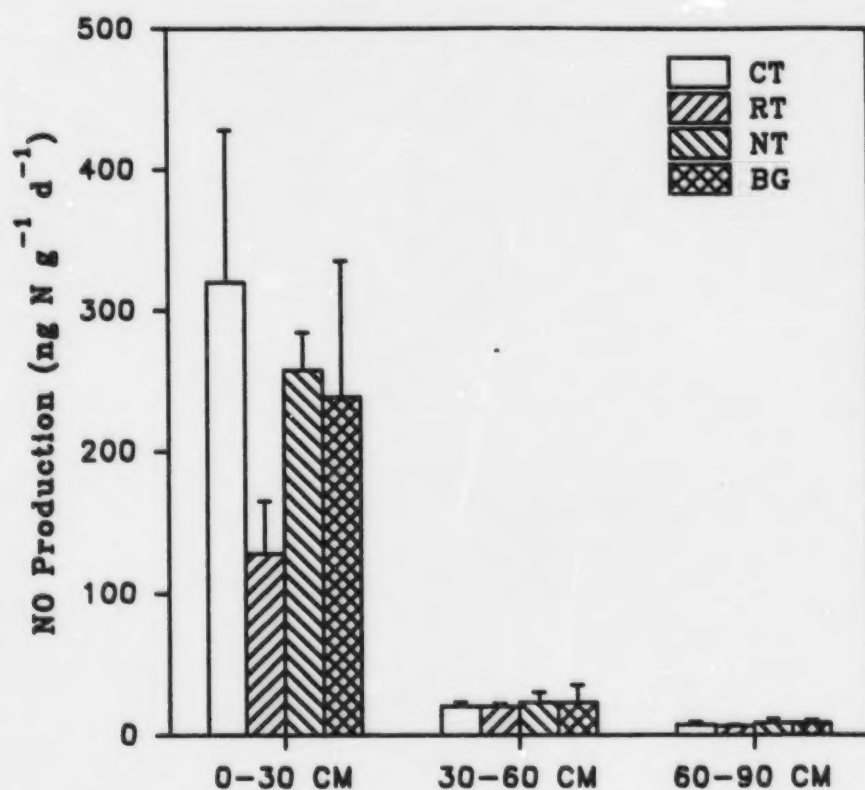


Figure 2.1

Background nitric oxide production rates of intact soil cores for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky Bluegrass (BG) soils in August, 1989.

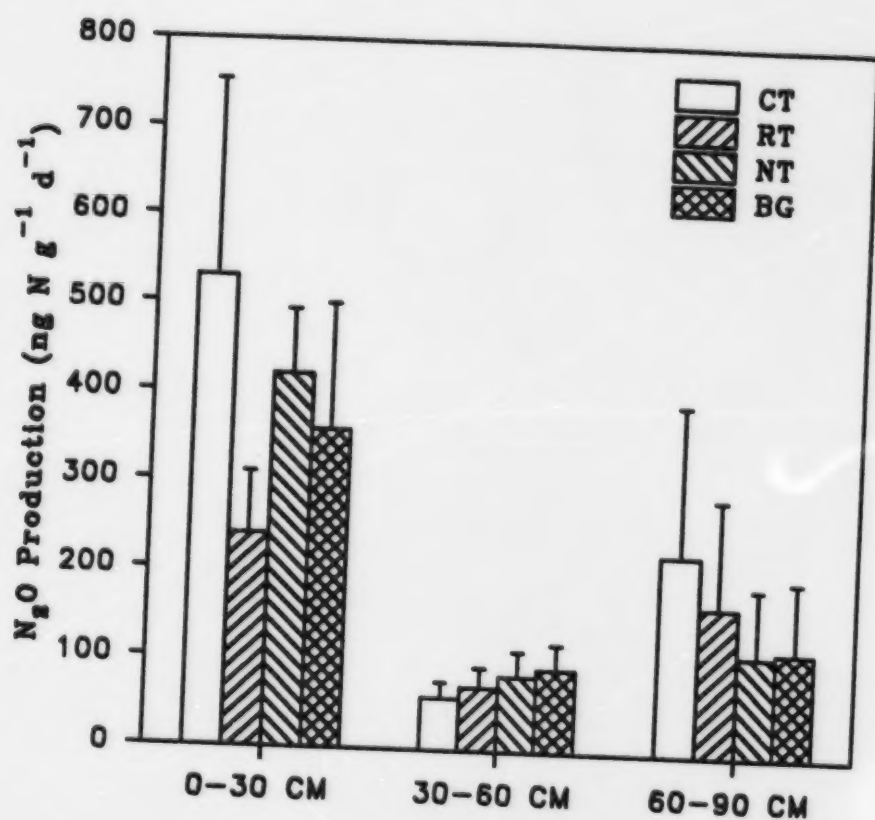


Figure 2.2 Background nitrous oxide production rates of intact soil cores for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky Bluegrass (BG) treatments in August, 1989.

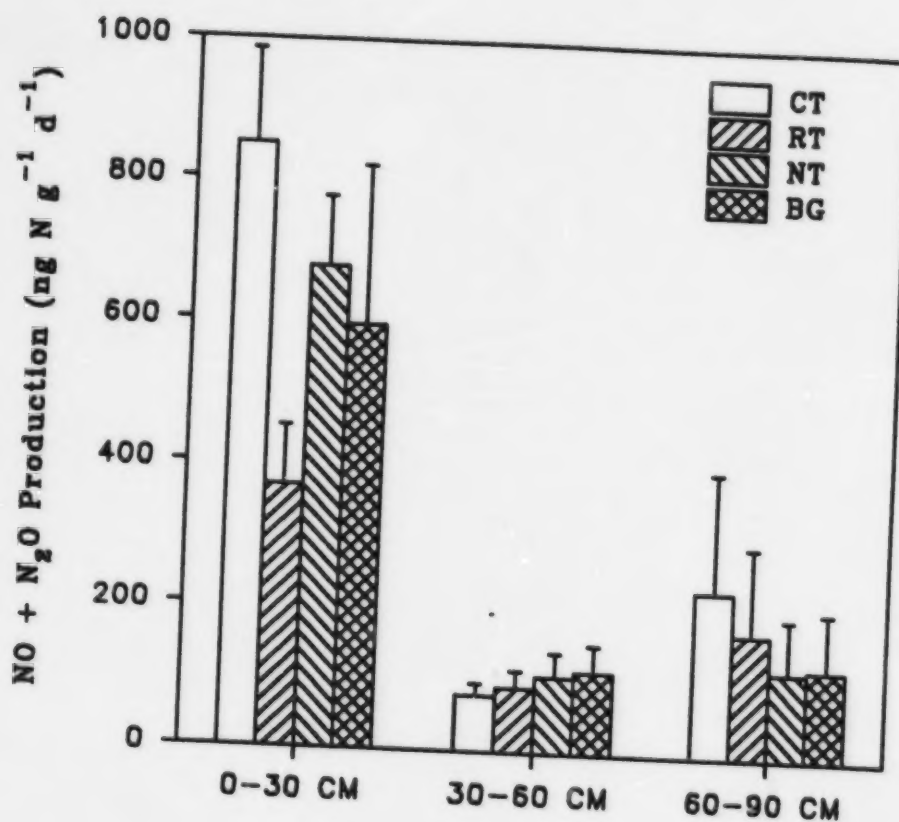


Figure 2.3

Total nitric plus nitrous oxide production rates of intact soil cores for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky Bluegrass (BG) treatments in August, 1989.

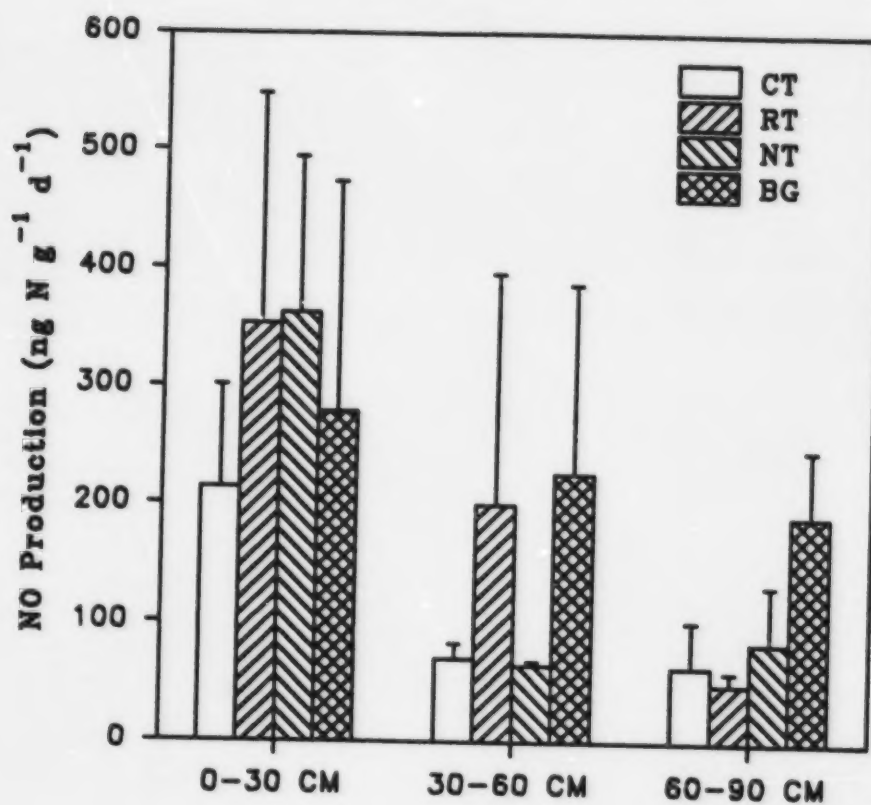


Figure 2.4 Background nitric oxide production rates in intact cores for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky Bluegrass (BG) soils in August, 1990.

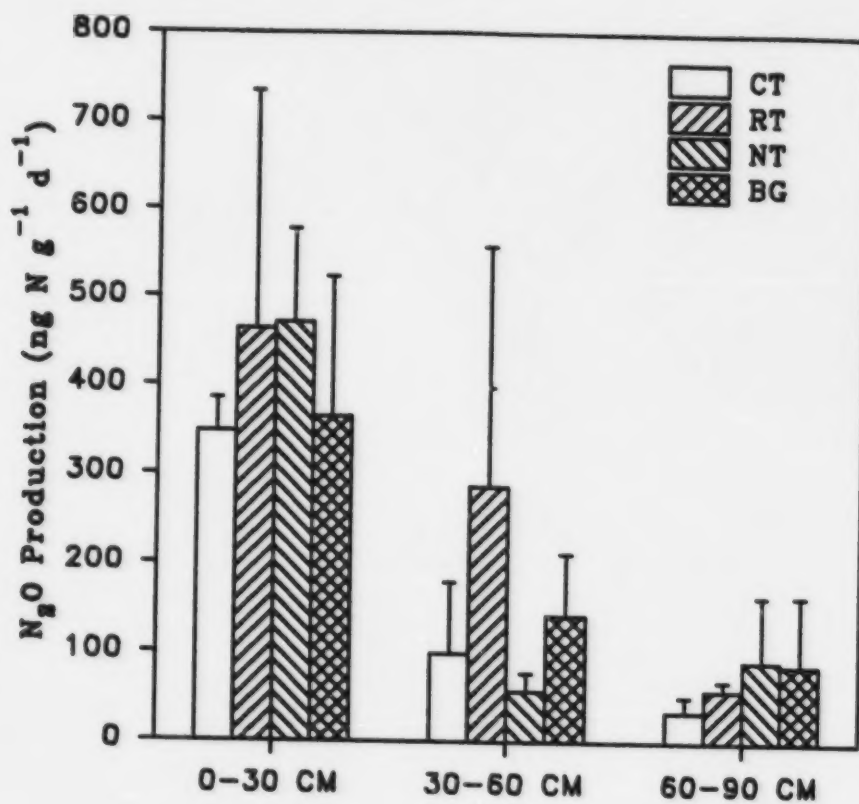


Figure 25 Background nitrous oxide production rates in intact cores for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky Bluegrass (BG) soils in August, 1990.

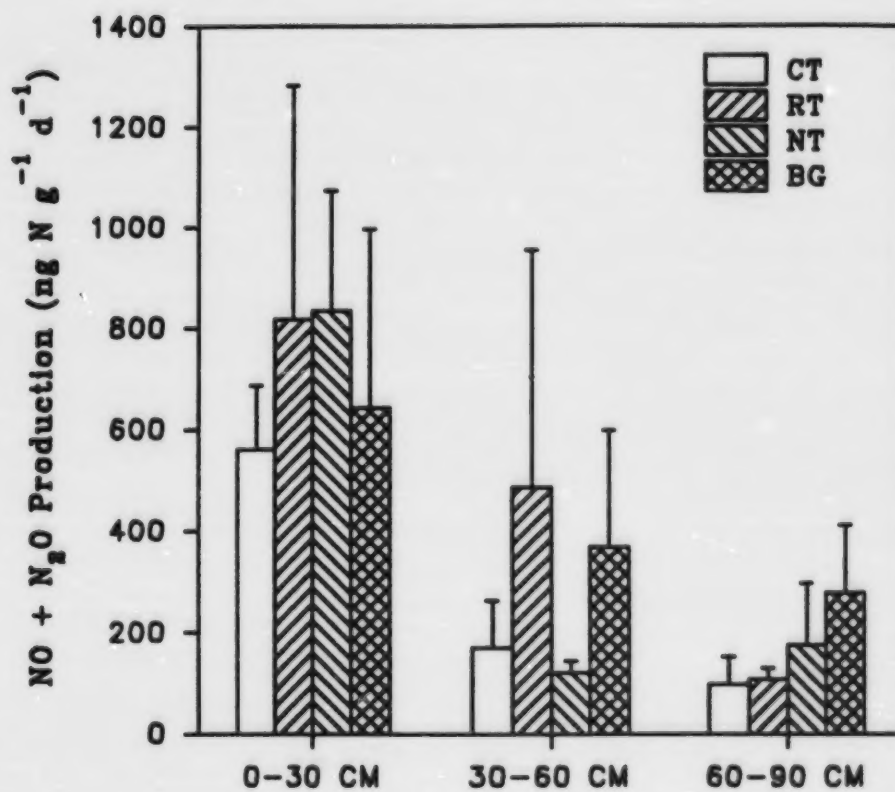


Figure 2.6 Total nitric oxide plus nitrous oxide production rates in intact cores for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky Bluegrass (BG) soils in August, 1990.

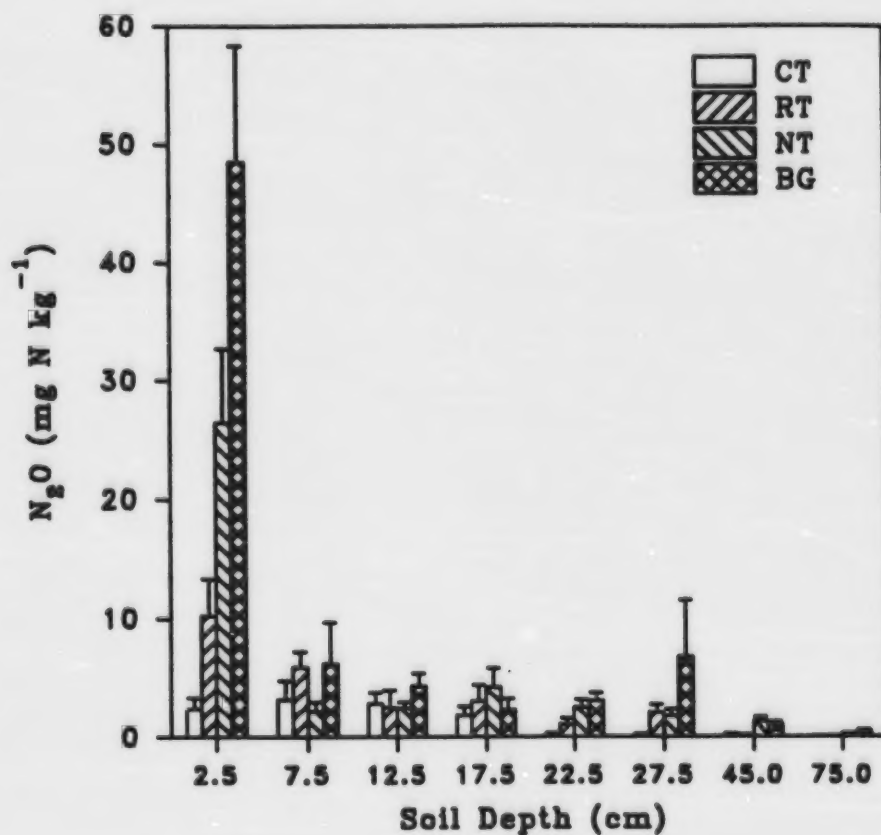


Figure 2.7 Nitrous oxide production from soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn row.

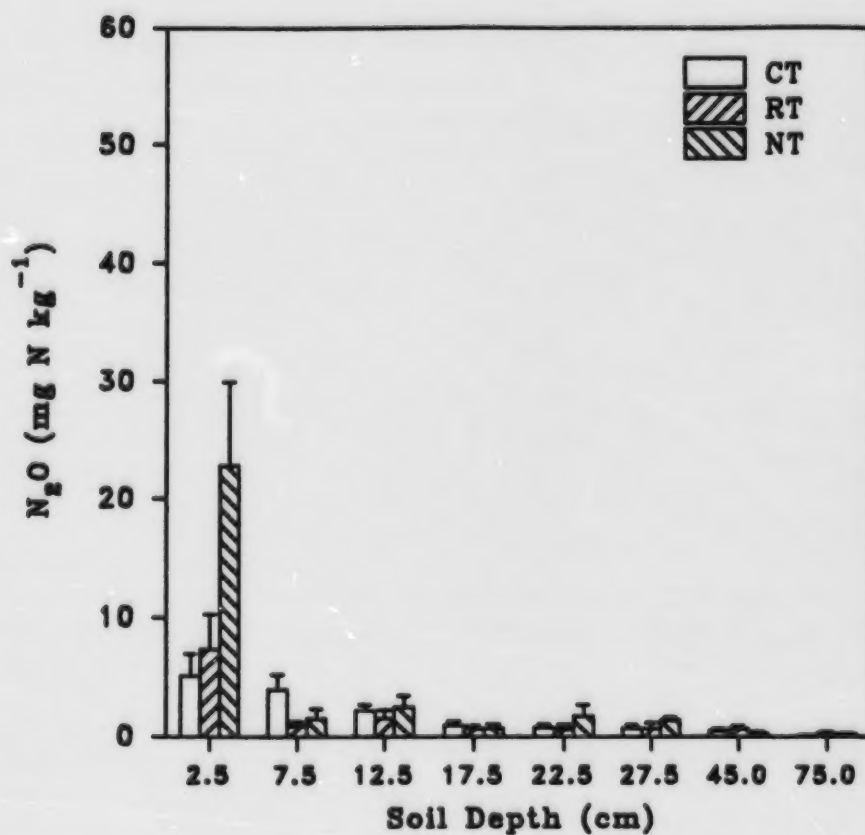


Figure 2.8 Nitrous oxide production from soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn interrow.

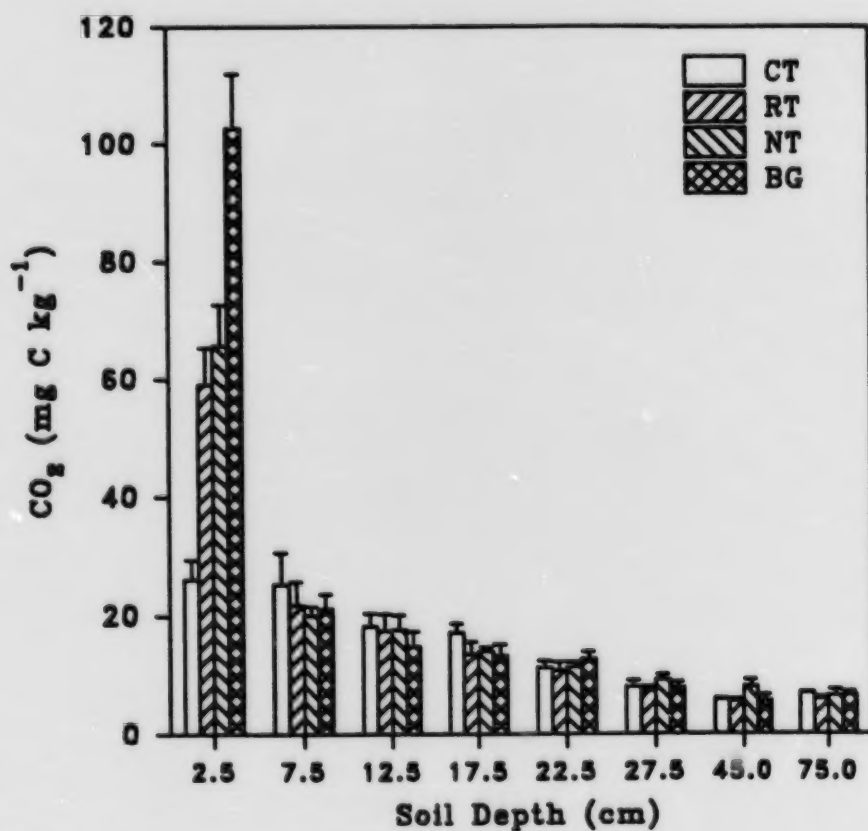


Figure 2.9 Carbon dioxide production from soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn row.

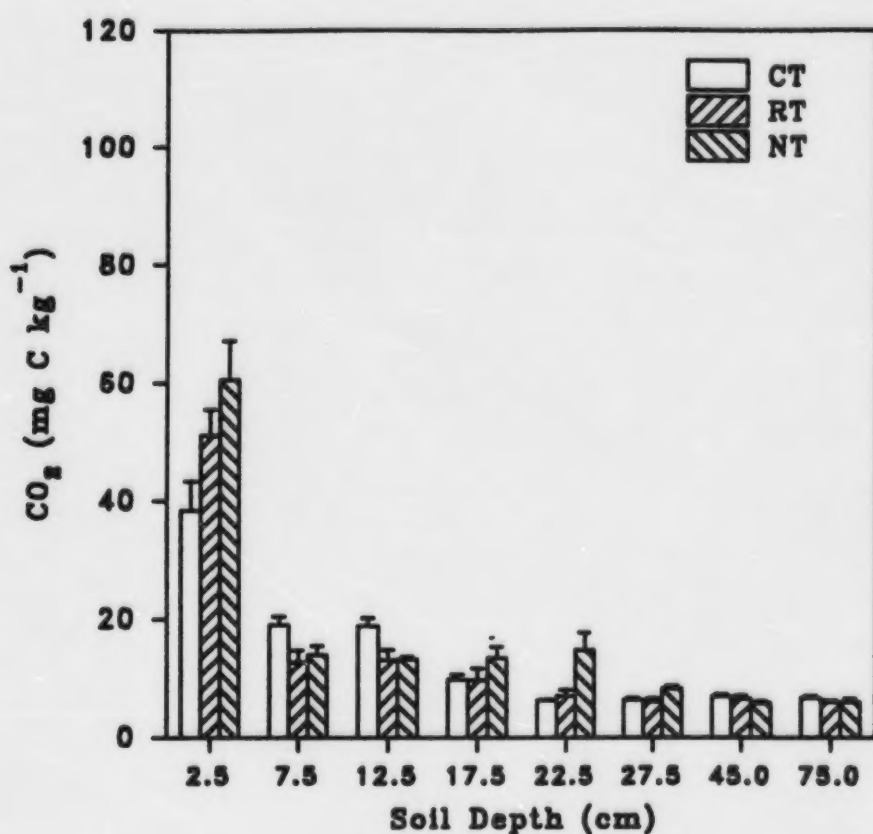


Figure 2.10 Carbon dioxide production from soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn interrow.

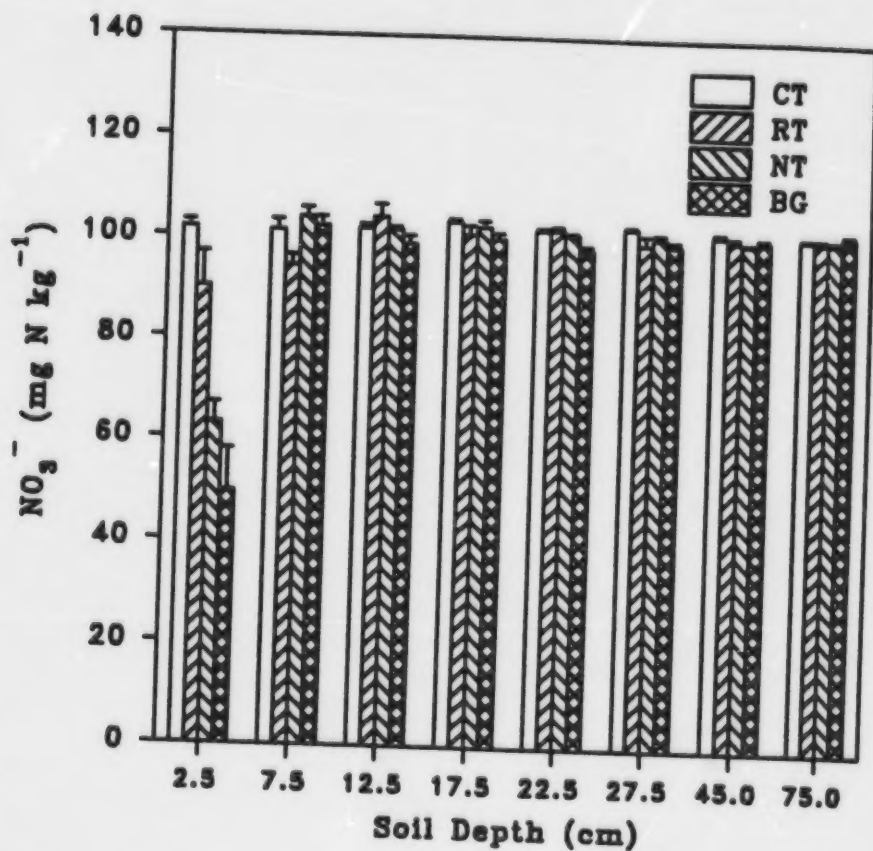


Figure 2.11 Nitrate concentrations in soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn row.

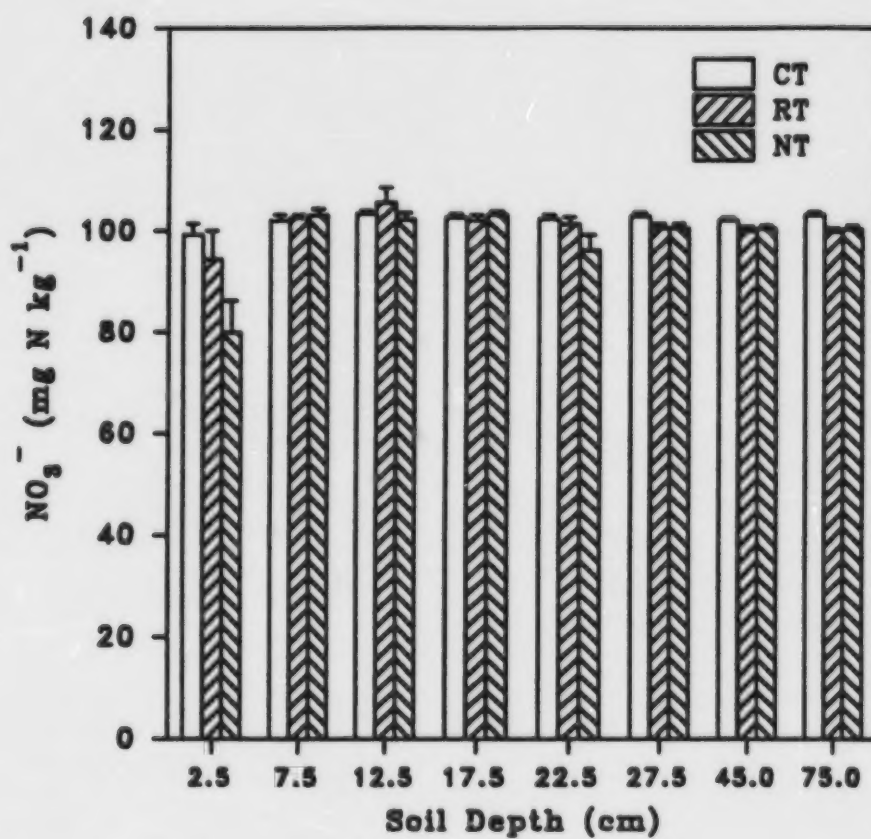


Figure 2.12 Nitrate concentration in soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn interrow.

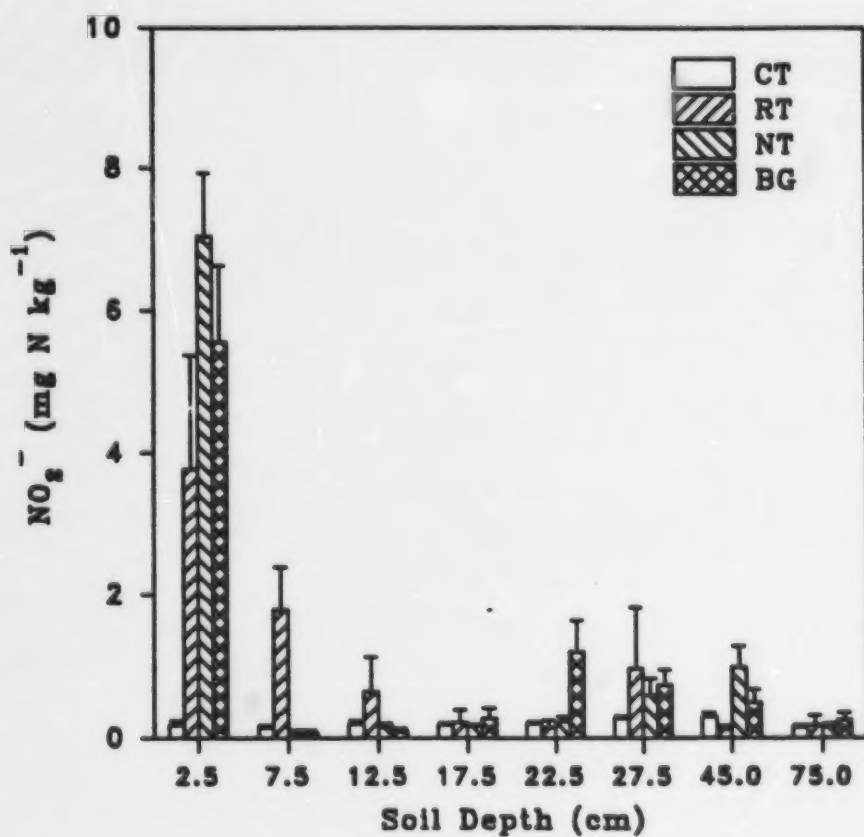


Figure 2.13 Nitrite concentration in soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn row.

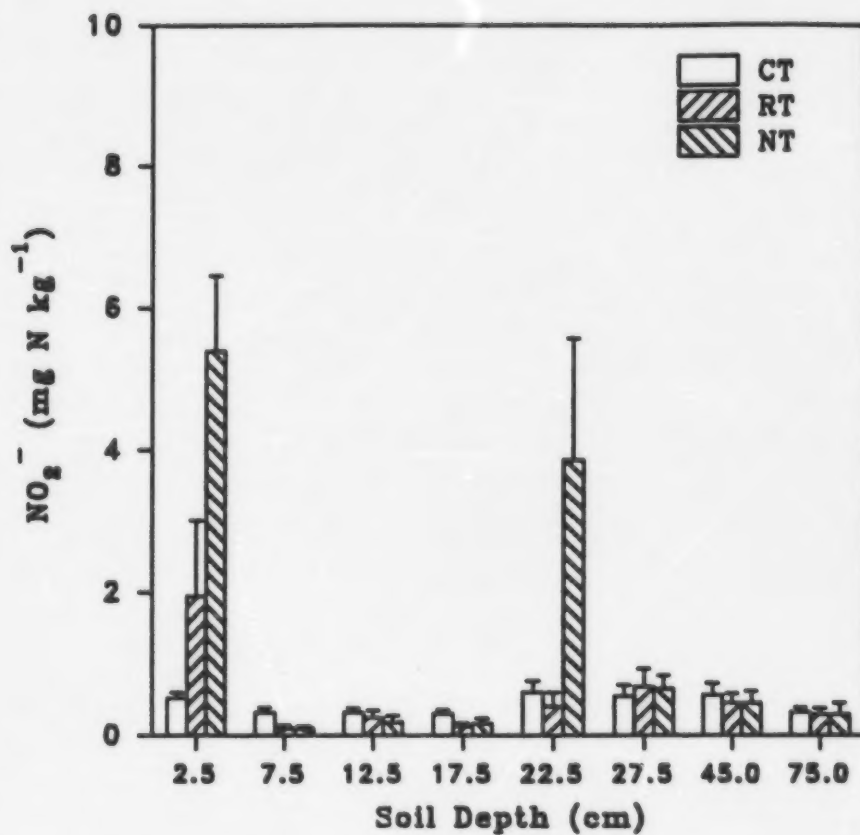


Figure 2.14 Nitrite concentration in soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn interrow.

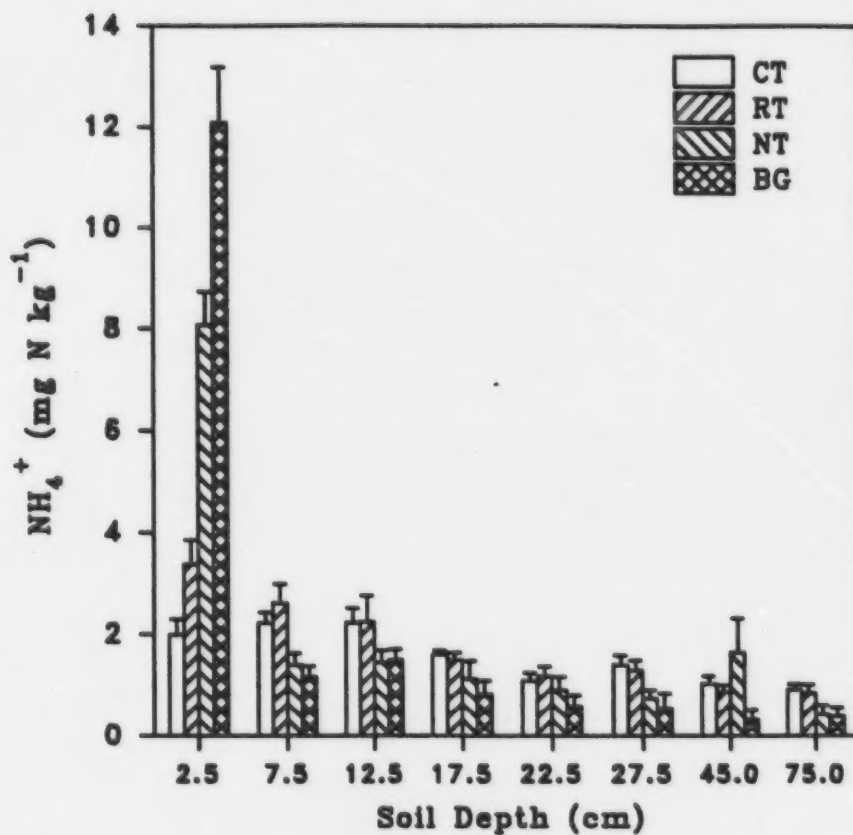


Figure 2.15 Ammonium concentration in soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn row.

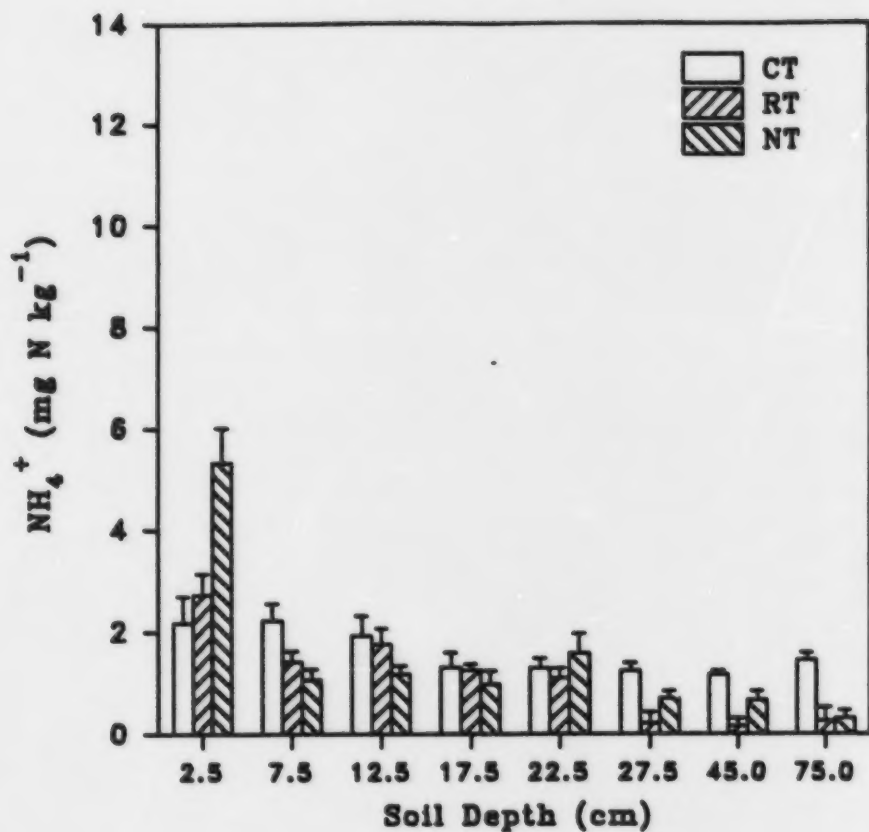


Figure 2.16 Ammonium concentration in soil at 0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-60 and 60-90 cm depth increments of a conventional till (CT), ridge till (RT), no-till (NT) and Kentucky bluegrass (BG) treatments. Sample cores were taken in the corn interrow.

### 3.0 NITRIC OXIDE AND NITROUS OXIDE PRODUCTION: WATER AND OXYGEN EFFECTS

#### 3.1 INTRODUCTION

Nitric oxide, nitrous oxide and dinitrogen are gaseous products of nitrification and denitrification processes and NO and N<sub>2</sub>O are important atmospheric trace gases. Nitric oxide (and NO<sub>2</sub>) in the troposphere catalyses photochemical ozone production, contributes to formation of acid rain and controls the formation of hydroxyl radicals, the major reactant for a number of atmospheric constituents (Parrish et al., 1990). Nitrous oxide is an important greenhouse gas and the major source of stratospheric NO, one of the predominant catalysts for ozone removal. The molar ratio of nitric oxide and nitrous oxide was found to be greater than one in nitrifier cultures whereas it has been found to be less than one for cultures of denitrifiers (Anderson and Levine, 1986). This may be the result of the influence of O<sub>2</sub> on denitrification. Nitric oxide production was found to be independent of pO<sub>2</sub> with nitrifiers whereas N<sub>2</sub>O production was inversely related to pO<sub>2</sub> for the denitrifiers.

The primary effect of water on denitrification in aerobic and partially aerobic soils is to restrict O<sub>2</sub> levels by reducing the air-water interfacial area within air-filled pores (Skopp, 1985) thus producing the anaerobic condition thought to be required for denitrification. Oxygen diffusion rates are some four orders of magnitude slower in water than in the gas phase and hence O<sub>2</sub> concentration at the microbial cell is regulated by water content (Klemedtsson et al., 1988). Relatively small changes in water content in soils may directly influence rates of denitrification. Many field studies have shown that intense denitrification activity often follows heavy rainfall or flooding periods when aeration of the soil is severely restricted (Sextstone et al., 1985).

Excess water not only limits O<sub>2</sub> diffusion into the soil, but also affects the movement, distribution and relative proportion of evolved denitrification gases. For example, Mahendrappa and Smith (1967) reported that a 10% increase in water content above field capacity in fully anaerobic

soils markedly increased the amount of  $N_2O$  converted to  $N_2$  with little effect on  $NO_3^-$  disappearance. Water contents above these levels further decreased rates of  $N_2O$  production.

The objective of this study was to investigate the physical effects of water on  $NO$  and  $N_2O$  production under conditions favoring denitrification using a gas flow column approach (McKenney et al., 1982). With this technique,  $NO$  and  $N_2O$  are rapidly scrubbed from the water and pore space in soil columns by a continuous flow of an inert carrier gas, enabling us to determine the production rates of these denitrification gases. In addition, the combined effect of  $O_2$  and soil water content on  $NO$  production was investigated.

### 3.2 MATERIALS AND METHODS

#### 3.2.1 Anaerobic $NO$ and $N_2O$ production at varying water contents

The Fox sandy loam (Typic Hapludalf) and the Brookston clay loam (Typic Haplaquoll) soils were chosen for this study. The average textural analyses for the Brookston soil is 290 g  $kg^{-1}$  sand, 350 g  $kg^{-1}$  silt, and 360 g  $kg^{-1}$  clay whereas there was 730 g  $kg^{-1}$  sand, 202 g  $kg^{-1}$  silt and 68 g  $kg^{-1}$  clay for the Fox soil. Soil pH using a 1:1 soil:water ratio averaged 6.1 and 5.5 for the Brookston and Fox soils, respectively. Soil was sieved through a 2mm sieve and then air dried to approximately 4% gravimetric content. The air-dried soil samples (100 g oven dried basis 105 °C) were weighed and distilled water was added to the soils to 5, 10, 15, 20 and 25% water content (gravimetric) including the water added with the potassium nitrate solution and these were packed into the columns to obtain bulk densities of approximately 1.2 and 1.0 g  $cm^{-3}$  for the Brookston and Fox soils, respectively. The Brookston soil had two additional moisture regimes at 30 and 35% water content. Soil water contents at 30% or higher for the Fox sandy loam restricted gas flow through the soil columns which hindered gas flow to the  $NO$  analyzer. Hence  $NO$  production could not be measured at high water contents for the Fox sandy loam with this technique. Potassium nitrate (100 mg N  $kg^{-1}$ ) solution was

subsequently added to each soil. Soil at the varying water contents was added to the columns. The columns had an outer water-filled jacket which was maintained at a constant temperature ( $20 \pm 0.1$  °C) with a constant temperature bath and pump. Humidified  $N_2$  gas flowed through the soil at  $390 \text{ cm}^3 \text{ min}^{-1}$ . Net production rates of NO and  $N_2O$  from these soil columns were measured at 0.25, 2, 5, 9, and 24 h following the typical pattern of rise and fall described previously (McKenney et al., 1982). Rates were calculated from the equation:

$$\text{net NO production rate} = \frac{[\text{NO}] \text{ fc}}{m}$$

where:       fc is the total flow rate ( $\text{mL min}^{-1}$ ) into the analyzer  
                   m is the oven-dry mass (kg) of soil.

A similar expression was used for  $N_2O$  rates. Nitric oxide was analyzed with a chemiluminescent NO/ $NO_2$ / $NO_x$  analyzer (model 14B/E Thermo Electron Corporation, Hopkinton, MA) and 1 mL gas samples were analyzed for  $N_2O$  using a porapak Q column on a Hewlett Packard (model 5880A, Avondale, Pa) gas chromatograph fitted with an electron capture detector. After 24 h, moist soil samples were removed from the columns. Moist soil (15 g) from each column was weighed into a 250 mL erlenmeyer flask and 100 mL 2M KCl added. The flasks were shaken for 1 h on a rotary shaker and the extractant filtered through Whatman # 40 filter paper and stored at 4 °C. The extracts were analyzed on a TRAACS 800 autoanalyzer for  $NH_4^+$  using the Berthelot reaction (Technicon industrial method 780-86T, Tarrytown, N.Y., U.S.A.). The extracts were also analyzed for  $NO_3^-$  plus  $NO_2^-$  with a Cd reduction column and  $NO_2^-$  alone without the column (Technicon industrial method 818-87T, Tarrytown, N.Y., U.S.A.). Nitrate content was calculated by difference.

### 3.2.2 Partially aerobic NO and N<sub>2</sub>O production at varying water contents

Air-dried soil samples (100 g oven dried basis 105 °C) were weighed and distilled water added to 10, 15, 20 and 25% water content (gravimetric) for the Fox soil whereas the moisture regimes for the Brookston soil were 10, 20, 30 and 35% water content (including the water contained with the KNO<sub>3</sub>). Potassium nitrate (100 mg N kg<sup>-1</sup>) solution was subsequently added to each soil. Soil at the varying water contents was added to the thermostatted (20±0.1 °C) columns. Humidified N<sub>2</sub> gas was flowed through the soil at 390 cm<sup>3</sup> min<sup>-1</sup> and steady state NO production was established. Oxygen was then added with the carrier gas (either 0.3, 1 or 5% O<sub>2</sub>) and when a new steady state flux occurred (usually within 0.5 h after the addition of O<sub>2</sub>), the NO flux was measured. Oxygen was then turned off and the NO flux returned to about the same level of production as occurred before the addition of O<sub>2</sub>. The relative effect of O<sub>2</sub> on NO production was calculated on the basis of the decrease in NO flux with the particular O<sub>2</sub> treatment relative to the NO flux with the anaerobic treatment (0% O<sub>2</sub>) as follows:

$$\Delta f_{\text{NO}} = f_{\text{NO}} (x \text{ O}_2 \text{ treatment}) - f_{\text{NO}} (0\% \text{ O}_2 \text{ treatment})$$

where x is either the 0.3, 1 or 5% O<sub>2</sub> treatment

## 3.3 RESULTS

### 3.3.1 Anaerobic NO and N<sub>2</sub>O production at varying water contents

Increasing water content enhanced the conversion of NO to N<sub>2</sub>O. (Figs. 3.1 and 3.2). Nitric oxide production increased with increasing water to a maximum at 10% water content with the Fox soil and 15% water content with the Brookston soil (Fig. 3.1). There was a rapid decrease in the amount of NO evolved at water contents above these maxima. Nitrous oxide production increased proportionally to increasing water content for the Brookston and Fox soils except for a subsequent

decrease at 25% water content for the Fox soil (Fig. 3.2). Similar amounts of  $N_2O$  were produced for the Brookston and Fox soils for the 5 to 20% water contents.

Generally, the total NO plus  $N_2O$  produced with the Brookston soil increased with increasing water content (Fig. 3.3). With the Fox soil, the total NO plus  $N_2O$  production increased to a maximum at 15% water content and subsequently decreased. At low water contents (5%) the ratio of NO to  $N_2O$  was about 35:1 in the Fox soil and 41:1 in the Brookston soil (Fig. 3.4). Similar amounts of NO and  $N_2O$  (i.e. NO: $N_2O$  about 1) were produced for the Brookston soil when the water content was between 20 to 30% and for the Fox soil when the water content was between 20 to 25%. More  $N_2O$  was produced than NO at 35% water contents in the Brookston soil.

All treatments had in excess of 100 mg N  $kg^{-1}$   $NO_3^-$  remaining at the end of the experiment except for the Brookston soil at 35% water content which had 85 mg N  $kg^{-1}$  (data not presented). Hence  $NO_3^-$  was not limiting in this experiment. The  $NH_4^+$  levels did not vary appreciably during this experiment with a range of 5 to 6 mg N  $kg^{-1}$  in the Fox soil and 6 to 11 mg N  $kg^{-1}$  in the Brookston soil.

### 3.3.2 Partially aerobic NO and $N_2O$ production at varying water contents

In the Fox soil, NO flux decreased the most when 5%  $O_2$  was mixed with the carrier gas and the flux changed the least at 0.3%  $O_2$  (Fig. 3.5). Oxygen had the greatest effect on decreasing NO production at low soil water contents. Nitric oxide production with the three  $O_2$  concentrations converged at the higher soil water contents. The 5%  $O_2$  treatment resulted in the greatest decrease in NO flux for the Brookston soil while the change was not as pronounced with 1 and 0.3%  $O_2$  treatments (Fig. 3.6). For each  $O_2$  regime, similar NO fluxes were observed at 10 and 20% water content. When the water content was increased to 30 and 35%, the change in NO flux was reduced especially for the 1 and 5%  $O_2$  regimes.

### 3.4 DISCUSSION

In the steady state flow system, the rates of production of NO and N<sub>2</sub>O are balanced by their removal by carrier gas and by any further reaction within the soil column (McKenney et al., 1982). In a flow column system, the outside surface of the water film is turbulent as a result of the high flow rate (390 cm<sup>3</sup> min<sup>-1</sup>) of the carrier gas through the moist soil. Hence the denitrification gases are scrubbed very rapidly. Since NO and N<sub>2</sub>O have limited solubility (Bunsen adsorption coefficients of 0.047 and 0.632, respectively, Tiedje, 1982), the water functions as a barrier to the passage of these gases to the gas phase and removal with the carrier gas. Increasing the water film thickness increases the time required for NO and N<sub>2</sub>O to diffuse into the gas phase and hence increases the potential for conversion of NO to N<sub>2</sub>O. Subsequent conversion of N<sub>2</sub>O to N<sub>2</sub> is also enhanced at higher water contents.

The decrease in NO plus N<sub>2</sub>O production under anaerobic conditions in the Fox soil at high water contents was probably due to the enhanced formation of N<sub>2</sub> from N<sub>2</sub>O. Presumably this would have also been observed in the Brookston soil if water contents greater than 35% were included in this study. Since the Brookston soil is a fine textured soil, the surface area of the soil particles is greater than with the Fox soil. For a particular water content, the thickness of the water film surrounding the soil particles would be less with the Brookston soil than the Fox soil. The film of water surrounding the particles in the Fox sand at 25% water content was probably thick enough to limit both NO and N<sub>2</sub>O diffusion and thereby facilitated N<sub>2</sub>O reduction to N<sub>2</sub>.

The relative amounts of the gaseous denitrification species were found to change with increasing water content. Soils under anaerobic conditions with low water contents had more NO than N<sub>2</sub>O as denitrification end products. At intermediate water regimes (20 to 30%) there were similar amounts of NO and N<sub>2</sub>O produced (i.e. NO:N<sub>2</sub>O, about 1:1). Soils with higher water contents produced more N<sub>2</sub>O than NO, and N<sub>2</sub> formation was likely favored at higher water contents.

Anaerobic soil conditions at low water contents may exist when residues are incorporated into the soil. In some situations such as when cellulose was added to soils, initial high  $O_2$  levels stimulate cellulose hydrolysis and mineralization and increase the demand for electron acceptors (Gok and Ottow, 1988). In this situation, microorganisms would use both  $O_2$  and  $NO_3^-$  as electron acceptors presumably in different microsites and by different organisms. Further, entrapped pockets of gas resulting from discontinuities in the pore space may lead to anaerobiosis in soils even at low water contents.

Rewetting dried soils can also stimulate denitrification, an effect which is correlated with increased C and N mineralization. This effect is caused by the stress imposed on the microbial biomass from the drying and rewetting process (Groffman and Tiedje, 1988). Drying soil increases the soils capacity to denitrify by increasing the amount of readily available organic carbon (Patten et al., 1980). In our study, soil water treatments were accomplished by rewetting the air dried soils (4% gravimetric water content). Carbon release from the drying-rewetting process and possible variation in the  $C:NO_3^-$  ratios may have contributed to the stimulation of denitrification losses.

The relative change in the total amount of N denitrified is dependent upon antecedent moisture conditions (Groffman and Tiedje, 1988). Hysteresis was observed in their study whereby a dramatic decrease in denitrification occurred when moist soils were dried whereas wetting dry soils resulted in a dramatic increase in the amount of N denitrified. We also observed an increase in denitrification when dry soils were moistened. Presumably the relative denitrification rates reported herein would have also demonstrated a hysteretic response if we used a drying treatment to obtain the water contents.

In the first experiment, anaerobic conditions were maintained with all treatments hence the effect of soil water content on total denitrification losses and denitrification gas speciation was independent of  $O_2$  effects. In the second experiment, both water content and  $O_2$  concentrations were

varied. For this reason, the effect of  $O_2$  on NO production rates were calculated relative to the anaerobic treatment to more easily separate  $O_2$  effects from soil water effects.

The concentration of  $O_2$  at the site of denitrification is affected by the quantity of  $O_2$  dissolved into the water which is proportional to the partial pressure of  $O_2$  in the carrier gas; the thickness of the layer of water which restricts  $O_2$  diffusion from the air-water interface to the microbial cell; and the amount of  $O_2$  consumed through microbial respiration. In general, NO inhibition by  $O_2$  was proportional to the concentration of  $O_2$  in the carrier gas. In this study,  $O_2$  effectively inhibited NO production at low soil water contents but was increasingly ineffective at higher soil water contents. Oxygen was more effective in depressing NO production in the Fox than in the Brookston soil. This may be due to the greater number of macropores and rapid diffusion of  $O_2$  to the microbes in the Fox sandy loam soil. While we can not preclude the possibility that an increase in microbial respiration and increased  $O_2$  consumption in response to C release on rewetting may favor differing extents of denitrification in the two soils, the data indicates that  $O_2$  diffusion to the microbial cell within each soil was restricted as the thickness of the water film surrounding the soil particles increased.

The ratio of  $NO:N_2O$  was a function of soil water level with greater levels of NO evolved in drier soils and relatively greater levels of  $N_2O$  evolved in wetter soils. Hence the speciation of evolved denitrification gas and corresponding environmental impacts are influenced by moisture regime.

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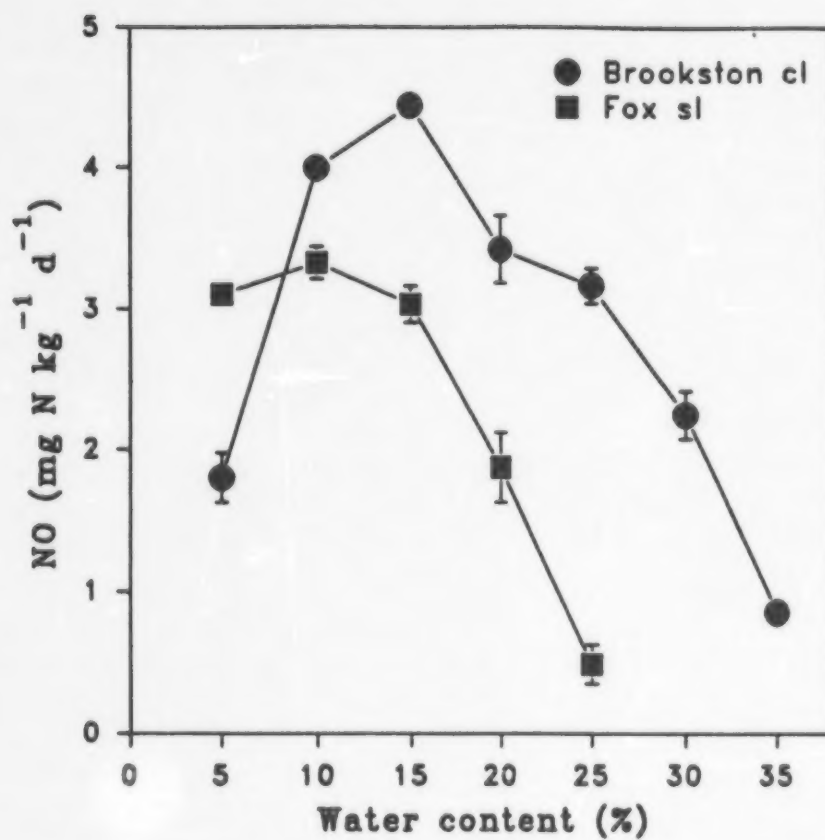


Figure 3.1 Nitric oxide production at varying gravimetric water contents for the Brookston clay loam and the Fox sandy loam soils under anaerobic conditions. The vertical bars are standard errors ( $n=3$ ).

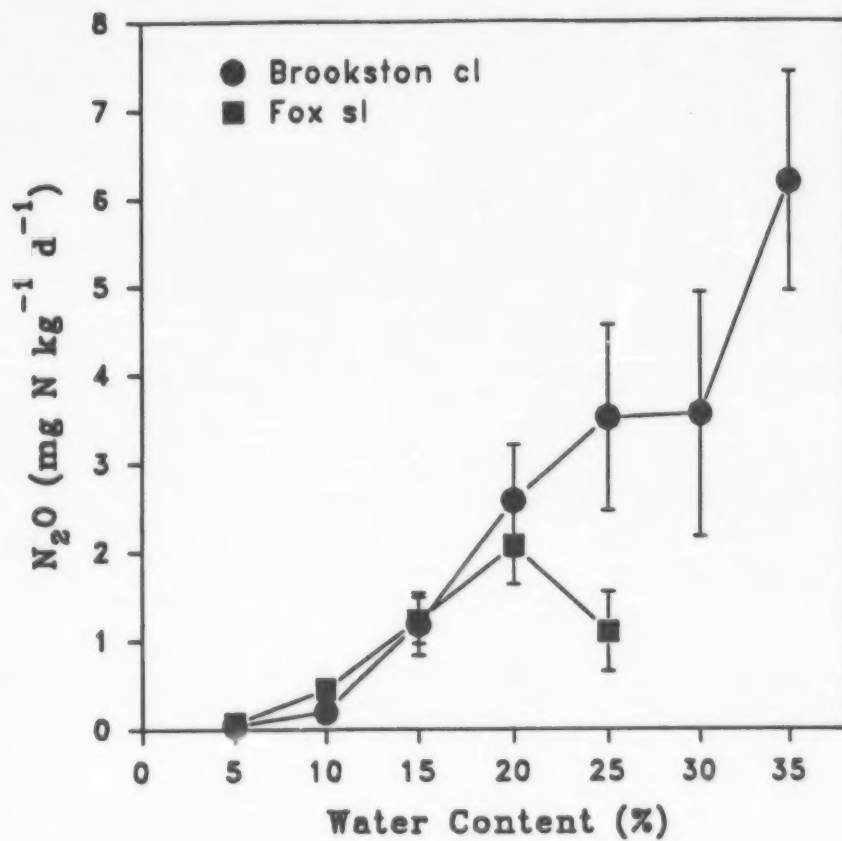


Figure 3.2 Nitrous oxide production at varying gravimetric water contents for the Brookston clay loam the Fox sandy loam soils under anaerobic conditions. The vertical bars are standard errors ( $n=3$ ).

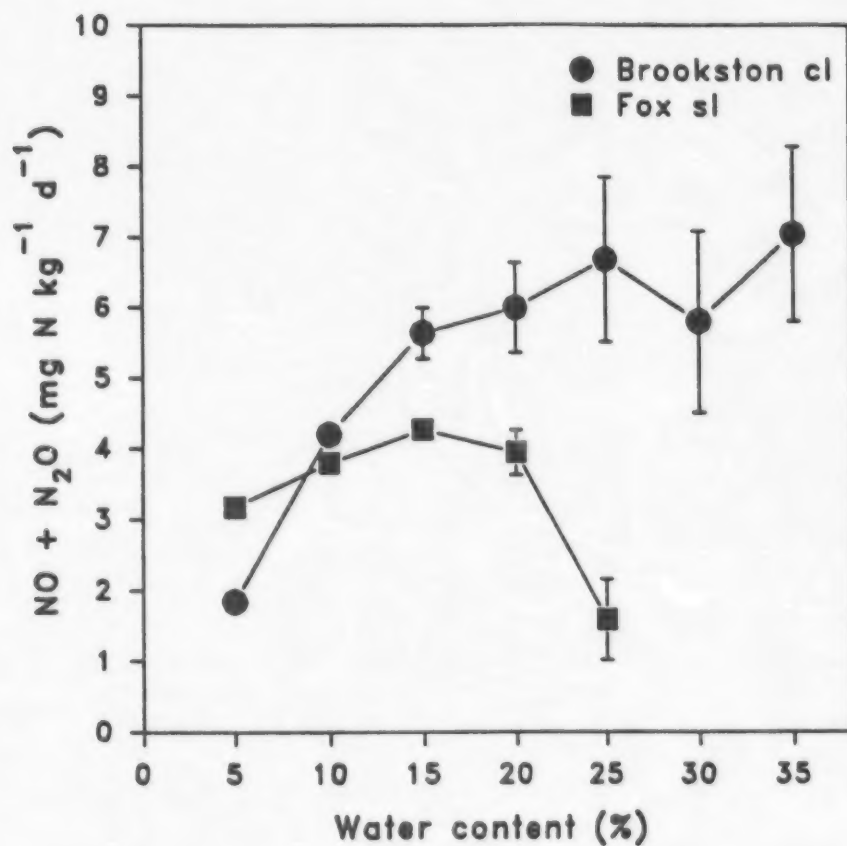


Figure 3.3 Nitric plus nitrous oxide production at varying gravimetric water contents for the Brookston clay loam and the Fox sandy loam soils under anaerobic conditions. The vertical bars are standard errors ( $n=3$ ).

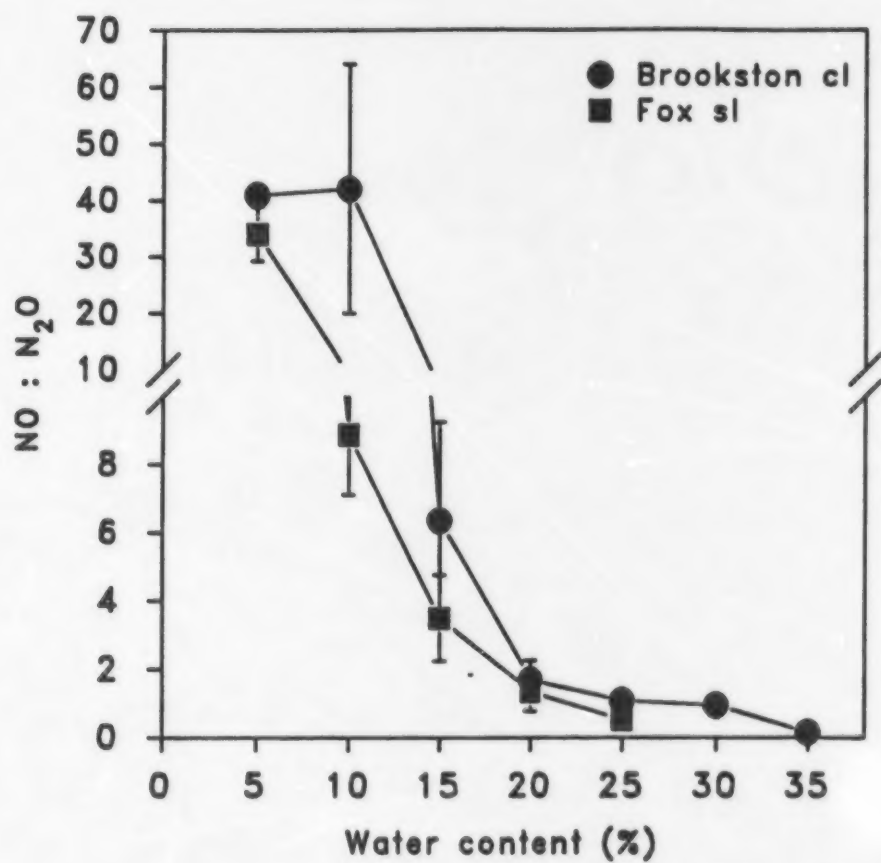


Figure 3.4 The ratio of NO:N<sub>2</sub>O at varying gravimetric water contents for the Brookston clay loam and the Fox sandy loam soils under anaerobic conditions. The vertical bars are standard errors (n=3).

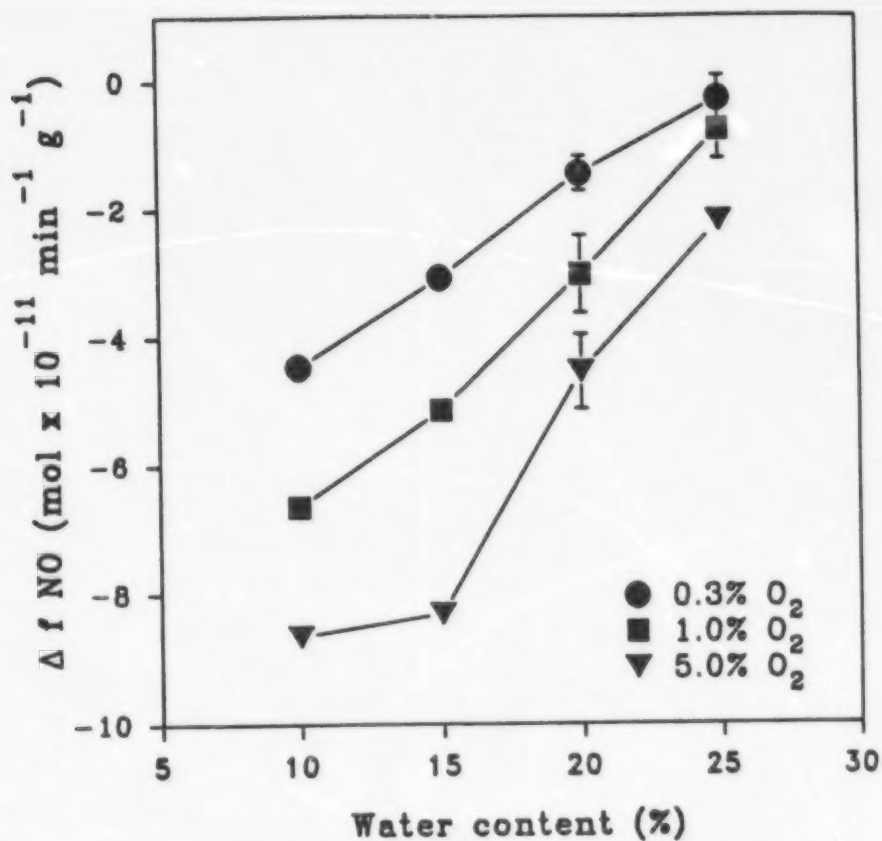


Figure 3.5

The decrease in NO production,  $\Delta f_{\text{NO}}$  with O<sub>2</sub> addition (0.3, 1 and 5%) at varying gravimetric water contents in the Fox sandy loam soil. The vertical bars are standard errors (n=3).

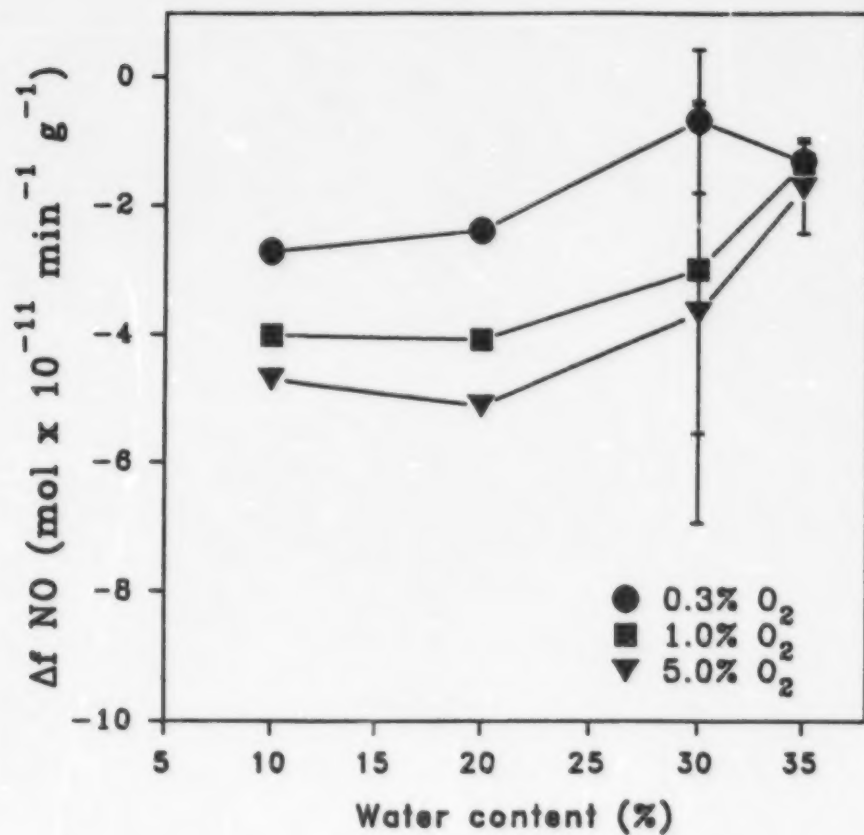


Figure 3.6 The decrease in NO production,  $\Delta f_{\text{NO}}$  with  $\text{O}_2$  addition (0.3, 1 and 5%) at varying gravimetric water contents in the Brookston clay loam soil. The vertical bars are standard errors ( $n=3$ ).

## APPENDIX A1 SOIL INORGANIC NITROGEN LEVELS IN CONSERVATION AND CONVENTIONAL TILLAGE SYSTEMS

### A1.1 INTRODUCTION

As an adjunct to the studies of  $\text{NO}_3^-$  loss in surface and tile water runoff or by denitrification, we monitored the movement of N-fertilizer through the soil by analysis of soil samples at the surface and at 20 cm intervals to 1 m depth under the various tillage treatments.

### A1.2 MATERIALS AND METHODS

#### A1.2.1 Extractable ammonium, nitrate and nitrite in soil under conventional and conservation tillage

Soil samples were taken at 20 cm depth intervals to 1 m in August and October 1989, in July and October 1990 and in June and July 1991. For the 1989 and 1990 years three subsamples were taken from each plot at each depth. In 1991, surface soil samples were taken to 30 cm depth on June 20, 1 day prior to N fertilizer application and July 9 at 20 cm depth intervals to 1 m, eighteen days after N was added. Four subsamples were taken from each plot for the June 1 sampling and three samples for the July 9 sampling. For all samples gravimetric moisture content was determined. Samples of 20 g moist soil were weighed into a 250 mL erlenmeyer flask and 100 mL 2M KCL added. The flasks were shaken for 1 h on a rotary shaker and the extractant filtered through Whatman # 40 filter paper and stored at 4°C. The extracts were analyzed on a TRAACS 800 autoanalyzer (Bran + Luebbe, Elmsford, New York) for  $\text{NH}_4^+$  using the Berthelot reaction and for  $\text{NO}_3^-$  plus  $\text{NO}_2^-$  using the cadmium reduction method (Tel and Heseltine, 1990). Nitrite concentration was determined without the column and  $\text{NO}_3^-$  content was calculated by difference.

### A1.2.2 Microbial biomass carbon

Soils collected in August and October 1989 were analyzed for biomass C. The chloroform fumigation-incubation method was used to determine microbial biomass C in the soils (Jenkinson and Powlson, 1976). The biomass estimates were made following two treatments: an incubated control treatment (IC) and a fumigated-incubated treatment using chloroform vapor (FI). The chloroform used in this study was stabilized with heptachlor-epoxide. One set of moist soil samples (FI) were weighed (25 g oven-dry weight basis) into 250-mL jars in triplicate. A second set was weighed into 1 L-mason jars. Distilled deionized water was added to both sets to bring the soils to -33 kPa water potential. The mason jars were sealed with lids fitted with a suba-seal (William Freeman and Company Limited, Barnsley, England S75 6DH) to allow sampling of the headspace atmosphere. Fumigated soils were not re-inoculated before incubation. The 250 mL jars containing the FI samples were placed in a desiccator with a beaker containing 30 mL chloroform. The desiccator was evacuated to ensure that the atmosphere was saturated with chloroform vapor. After 24 h, the beaker of chloroform was removed and the desiccator was evacuated three times to ensure that the soils were free of chloroform.

The FI samples were transferred to 1 L-mason jars. Both sets of soils were incubated for 10 d at 25°C. At the end of the incubation period, 0.25-mL gas samples were removed with a syringe and analyzed for CO<sub>2</sub> using a Varian 3000 gas chromatograph equipped with a thermal conductivity detector. The following equation was used to calculate the various C fractions:

$$\text{Biomass C} = [(\text{CO}_2\text{-C})_n]/k_c$$

where  $k_c$  = proportionality coefficient used to estimate biomass C from CO<sub>2</sub> evolved. The  $k_c$  coefficient was assumed to be 0.45 (Jenkinson and Ladd, 1981).

## A1.3 RESULTS

### A1.3.1 Extractable ammonium, nitrate and nitrite in 1989

In August 1989,  $\text{NH}_4^+$  levels in all tillage systems were in the 2-3 mg N  $\text{kg}^{-1}$  range in the surface 0-20 cm layer and decreased to concentrations between 1-2 mg N  $\text{kg}^{-1}$  in the 60-100 cm depths (Fig. A.1). The Kentucky Bluegrass plot had higher levels in the 0-20 cm and 20-40 cm samples but had lowest levels at depths of 60-100 cm. These data show that in all tillage systems, nitrification of added N-fertilizer was virtually completed by the time these samples were obtained, 40 d after ammonium nitrate application. Some residual  $\text{NO}_3^-$  remained in the surface 0-20 cm depth in August (Fig. A.2). Except for the surface depth, CT corn had greater  $\text{NO}_3^-$  contents than RT and NT corn and the BG treatments. The  $\text{NO}_2^-$  concentrations in August (data not shown) were less than 0.2 mg N  $\text{kg}^{-1}$  for all treatments and depths. The soil was sampled again in October in the same manner as in August. Analyses of the October samples for  $\text{NH}_4^+$  showed similar trends to the August samples and those for  $\text{NO}_3^-$  showed similarity in two respects (Table A1). The ridge-till corn plot had the highest  $\text{NO}_3^-$  content (15.3 mg N  $\text{kg}^{-1}$ ) at the surface 0-20 cm depth. Nitrate levels decreased with depth under all plots with the lowest content under BG (2.4 mg N  $\text{kg}^{-1}$ ) at the 80-100 cm depth.

### A1.3.2 Extractable ammonium, nitrate and nitrite in 1990

In 1990 the  $\text{NH}_4^+$  content in the soil was less than 1 mg N  $\text{kg}^{-1}$  for all treatments and all depths with the July samples (Table A2). The BG plots had the greatest quantity of  $\text{NO}_3^-$  in the soil at the 20-40 and 60-80 cm depths. All other treatments and depths had less than 5 mg  $\text{NO}_3^-$ -N  $\text{kg}^{-1}$  in the soil. Nitrates were evenly distributed in the profile. The soil  $\text{NO}_2^-$  content for all treatments and depths was less than 0.2 mg N  $\text{kg}^{-1}$ . The  $\text{NH}_4^+$  and  $\text{NO}_3^-$  levels in October very low (<6 mg N  $\text{kg}^{-1}$ ) for all treatments (Table A3). The conventional till corn treatment had more  $\text{NO}_3^-$  than all other

treatments at all depths except for the 80-100 cm depth. Nitrate levels decreased with depth for the CT treatment. No systematic difference could be identified among samples taken from the corn row or from the inter-row.

### A1.3.3 Extractable ammonium, nitrate and nitrite in 1991

Before nitrogen was sidedressed in July 1991, the extractable  $\text{NH}_4^+$  and  $\text{NO}_3^-$  levels in the soil were very low (Fig's. A1-A3). The background  $\text{NH}_4^+$  levels ranged from 1.59 to 2.35 mg N  $\text{kg}^{-1}$  across treatments with the BG treatment containing the most  $\text{NH}_4^+$  and the conventional tilled treatment the least (Fig. A3). There was more nitrate in the soils under corn (between 2.58 and 4.74 mg N  $\text{kg}^{-1}$ ) than in the BG plots (1.36 mg N  $\text{kg}^{-1}$ ), (Fig. A4). The location of the sample in the plot (row vs inter-row) also did not significantly affect the background  $\text{NH}_4^+$  or  $\text{NO}_3^-$  levels. Insignificant differences in total  $\text{NH}_4^+ + \text{NO}_3^-$  levels exist among the corn plots ( $\sim 4.5$  to 7.0 mg N  $\text{kg}^{-1}$ ) with slightly lower concentrations  $\sim 3.8$  mg N  $\text{kg}^{-1}$  in the BG plots (Fig. A5).

The levels of  $\text{NH}_4^+$  in the soil were high with the CT treatment in the 0-20 cm depth with 27.8 mg N  $\text{kg}^{-1}$  in the corn row and 41.2 mg N  $\text{kg}^{-1}$  in the inter-row area (Fig A6). All other treatments had considerably less  $\text{NH}_4^+$ . There was 5.35 mg N  $\text{kg}^{-1}$   $\text{NH}_4^+$  in the 0-20 cm depth with the BG sod and less than 3 mg N  $\text{kg}^{-1}$  for all other treatments and depths. Nitrate levels in the soil were also highest with the CT corn treatment with 58.9 and 30.9 mg N  $\text{kg}^{-1}$  in the row and inter-row area (Fig A7). The NT and RT treatments had between 5.1 and 10.1 mg N  $\text{kg}^{-1}$  in the 0-20 cm depth and there was 3 mg N  $\text{kg}^{-1}$  or less for all treatments at all lower depths. The total  $\text{NH}_4^+$  and  $\text{NO}_3^-$  contents, shown in Fig. A8, were also greatest with the CT treatment averaging about eight times more inorganic nitrogen than with the reduced tilled treatments and 4.5 times more than the sod treatment at the 0-20 cm depth. All depths below the 0-20 cm depth contained between 2.0 and 5.3 mg N  $\text{kg}^{-1}$  total inorganic nitrogen.

Microbial activity was highest in the surface 0-20 cm depth but was present at significant levels, approximately 30-50 mg C kg<sup>-1</sup> at depths between 40 and 100 cm under all plots (Fig. A9). Conventional tillage corn plots had the lowest microbial biomass C, and NT corn the greatest biomass C although the standard errors overlapped for all but the CT corn.

#### A1.4 DISCUSSION

All data show that relatively low concentrations of NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup> and NO<sub>2</sub><sup>-</sup> remained in the soil in October. Low ammonium levels were not surprising as plant uptake, nitrification, immobilization and ammonium fixation by clay colloids depleted the extractable ammonium content in the soil (Drury et al., 1991). In addition to plant uptake and immobilization, nitrate depletion occurred as a result of nitrate leaching and denitrification.

The 1990 data show that nitrification was virtually completed by the first sampling period (July) as demonstrated by the low level of NH<sub>4</sub><sup>+</sup> in the soil with all treatments (Table A2). Nitrates were found at depths to 1m with all treatments indicating that it was being leached through the soil profile. In 1991 the severe drought limited the losses by leaching. The background soil inorganic nitrogen levels obtained in samples taken before nitrogen was sidedressed in July, indicated minimal carryover of inorganic nitrogen from the previous year. The levels of inorganic nitrogen in the soil samples obtained 18 days after N was added showed that the inorganic nitrogen content for the CT treatment was considerably higher than with all other treatments. This also corresponds with visual observations of poorer crop development than with the RT or NT plots. The final grain and fodder yields and N uptake confirmed these observations (Chapter 1). There was considerable variability with the NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> analysis of the 0-20 cm samples from the CT treatment. This may have been partially due to the variability in N uptake by the corn plants as well as slower diffusion rates of nitrate in the dry soil from the fertilizer zone to the corn row.

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Table A.1 Soil  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{NO}_2^-$  content at varying depths in October, 1989 with conventional till (CT), ridge till (RT) and no-till (NT) corn treatments and with Kentucky bluegrass (BG).

| Treatment | Depth  | $\text{NH}_4^+$       | $\text{NO}_3^-$ | $\text{NO}_2^-$ |
|-----------|--------|-----------------------|-----------------|-----------------|
|           |        | mg N $\text{kg}^{-1}$ |                 |                 |
| CT        | 0-20   | 2.31 (0.12)*          | 8.18 (1.37)     | 0.33 (0.04)     |
|           | 20-40  | 1.75 (0.11)           | 5.12 (0.63)     | 0.46 (0.08)     |
|           | 40-60  | 1.76 (0.15)           | 3.56 (0.45)     | 0.39 (0.09)     |
|           | 60-80  | 1.67 (0.10)           | 3.52 (0.43)     | 0.35 (0.11)     |
|           | 80-100 | 1.50 (0.11)           | 2.97 (0.44)     | 0.26 (0.07)     |
| RT        | 0-20   | 4.17 (1.09)           | 15.26 (3.52)    | 0.27 (0.10)     |
|           | 20-40  | 3.04 (0.67)           | 7.47 (1.78)     | 0.42 (0.07)     |
|           | 40-60  | 2.25 (0.52)           | 7.81 (1.66)     | 0.42 (0.13)     |
|           | 60-80  | 1.55 (0.14)           | 5.51 (0.95)     | 0.26 (0.06)     |
|           | 80-100 | 1.59 (0.25)           | 5.16 (0.74)     | 0.20 (0.08)     |
| NT        | 0-20   | 3.97 (0.60)           | 7.88 (0.92)     | 0.23 (0.03)     |
|           | 20-40  | 3.50 (0.73)           | 6.22 (0.71)     | 0.22 (0.02)     |
|           | 40-60  | 2.13 (0.16)           | 4.66 (0.79)     | 0.25 (0.04)     |
|           | 60-80  | 2.09 (0.24)           | 5.56 (0.96)     | 0.30 (0.05)     |
|           | 80-100 | 2.32 (0.43)           | 4.23 (0.84)     | 0.39 (0.05)     |
| BG        | 0-20   | 2.47 (0.12)*          | 12.25 (3.71)    | 0.19 (0.08)     |
|           | 20-40  | 1.67 (0.05)           | 4.32 (0.66)     | 0.13 (0.05)     |
|           | 40-60  | 1.51 (0.06)           | 2.93 (0.39)     | 0.19 (0.03)     |
|           | 60-80  | 1.34 (0.03)           | 2.65 (0.28)     | 0.14 (0.04)     |
|           | 80-100 | 1.20 (0.07)           | 2.35 (0.31)     | 0.10 (0.03)     |

\* All numbers in parenthesis are standard error (n=6).

Table A2. Soil  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{NO}_2^-$  content at varying depths in July, 1990 with conventional till (CT), ridge till (RT) and no-till (NT) corn treatments and with Kentucky bluegrass (BG).

| Treatment | Depth  | $\text{NH}_4^+$       | $\text{NO}_3^-$ | $\text{NO}_2^-$ |
|-----------|--------|-----------------------|-----------------|-----------------|
|           |        | mg N kg <sup>-1</sup> |                 |                 |
| CT        | 0-20   | 0.50 (0.02)*          | 3.29 (0.79)     | 0.12 (0.04)     |
|           | 20-40  | 0.51 (0.02)           | 4.27 (1.24)     | 0.11 (0.05)     |
|           | 40-60  | 0.55 (0.06)           | 4.13 (0.49)     | 0.06 (0.03)     |
|           | 60-80  | 0.64 (0.08)           | 1.64 (0.47)     | 0.07 (0.02)     |
|           | 80-100 | 0.51 (0.03)           | 5.67 (2.00)     | 0.10 (0.05)     |
| RT        | 0-20   | 0.49 (0.02)           | 4.67 (1.34)     | 0.06 (0.02)     |
|           | 20-40  | 0.73 (0.09)           | 4.41 (0.66)     | 0.08 (0.03)     |
|           | 40-60  | 0.65 (0.08)           | 0.86 (0.22)     | 0.01 (0.01)     |
|           | 60-80  | 0.87 (0.14)           | 4.83 (1.66)     | 0.05 (0.02)     |
|           | 80-100 | 0.83 (0.12)           | 3.46 (0.52)     | 0.08 (0.04)     |
| NT        | 0-20   | 0.52 (0.01)           | 3.53 (0.53)     | 0.05 (0.04)     |
|           | 20-40  | 0.62 (0.08)           | 0.38 (0.13)     | 0.05 (0.04)     |
|           | 40-60  | 0.67 (0.03)           | 3.23 (0.90)     | 0.03 (0.02)     |
|           | 60-80  | 0.62 (0.04)           | 4.21 (0.52)     | 0.08 (0.04)     |
|           | 80-100 | 0.58 (0.03)           | 4.84 (1.81)     | 0.11 (0.05)     |
| BG        | 0-20   | 0.74 (0.05)           | 3.17 (0.78)     | 0.04 (0.02)     |
|           | 20-40  | 0.84 (0.24)           | 13.11 (7.42)    | 0.10 (0.04)     |
|           | 40-60  | 0.55 (0.04)           | 3.23 (0.38)     | 0.15 (0.05)     |
|           | 60-80  | 0.50 (0.02)           | 9.95 (3.69)     | 0.03 (0.02)     |
|           | 80-100 | 0.79 (0.08)           | 2.42 (0.77)     | 0.03 (0.02)     |

\* All numbers in parenthesis are standard error (n=6).

Table A3. Soil  $\text{NH}_4^+$ ,  $\text{NO}_3^-$  and  $\text{NO}_2^-$  content at varying depths in October, 1990 with conventional till (CT), ridge till (RT) and no-till (NT) corn treatments and with Kentucky bluegrass (BG).

| Treatment | Depth  | mg N kg <sup>-1</sup> |                 |                 |                 |                 |                 |
|-----------|--------|-----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|           |        | $\text{NH}_4^+$       | $\text{NO}_3^-$ | $\text{NO}_2^-$ | $\text{NH}_4^+$ | $\text{NO}_3^-$ | $\text{NO}_2^-$ |
|           |        | Corn Row              |                 |                 | Inter-row       |                 |                 |
| CT        | 0-20   | 1.75 (0.20)*          | 5.42 (3.06)     | 0.20 (0.02)     | 1.77 (0.30)     | 1.99 (0.55)     | 0.09 (0.04)     |
|           | 20-40  | 1.23 (0.08)           | 4.49 (3.10)     | 0.18 (0.01)     | 1.03 (0.17)     | 2.22 (1.37)     | 0.60 (0.49)     |
|           | 40-60  | 0.94 (0.07)           | 2.78 (1.76)     | 0.17 (0.00)     | 0.90 (0.12)     | 2.21 (0.93)     | 0.07 (0.01)     |
|           | 60-80  | 1.17 (0.18)           | 1.99 (1.00)     | 0.16 (0.02)     | 0.92 (0.13)     | 1.53 (0.55)     | 0.07 (0.03)     |
|           | 80-100 | 1.11 (0.05)           | 1.07 (0.21)     | 0.17 (0.01)     | 1.00 (0.08)     | 1.08 (0.24)     | 0.08 (0.03)     |
| RT        | 0-20   | 2.16 (0.35)           | 2.54 (0.59)     | 0.17 (0.00)     | 1.68 (0.28)     | 1.79 (0.29)     | 0.09 (0.04)     |
|           | 20-40  | 1.47 (0.12)           | 1.62 (0.42)     | 0.18 (0.00)     | 1.18 (0.19)     | 2.57 (0.86)     | 0.04 (0.02)     |
|           | 40-60  | 1.38 (0.17)           | 0.83 (0.15)     | 0.16 (0.00)     | 0.94 (0.09)     | 3.26 (1.94)     | 0.04 (0.02)     |
|           | 60-80  | 1.31 (0.19)           | 0.76 (0.11)     | 0.17 (0.00)     | 1.25 (0.12)     | 2.22 (1.36)     | 0.13 (0.04)     |
|           | 80-100 | 1.45 (0.16)           | 1.19 (0.21)     | 0.17 (0.00)     | 1.55 (0.41)     | 0.92 (0.14)     | 0.13 (0.04)     |
| NT        | 0-20   | 1.73 (0.12)           | 1.30 (0.24)     | 0.18 (0.00)     | 1.21 (0.13)     | 1.90 (0.56)     | 0.09 (0.04)     |
|           | 20-40  | 1.18 (0.05)           | 0.87 (0.12)     | 0.18 (0.01)     | 1.06 (0.13)     | 2.11 (0.71)     | 0.09 (0.04)     |
|           | 40-60  | 1.10 (0.07)           | 0.66 (0.11)     | 0.21 (0.02)     | 0.94 (0.08)     | 1.64 (0.53)     | 0.09 (0.04)     |
|           | 60-80  | 1.26 (0.14)           | 0.61 (0.08)     | 0.21 (0.02)     | 0.98 (0.19)     | 0.92 (0.27)     | 0.08 (0.03)     |
|           | 80-100 | 1.32 (0.12)           | 0.60 (0.05)     | 0.23 (0.03)     | 0.99 (0.19)     | 0.73 (0.10)     | 0.08 (0.03)     |
| BG        | 0-20   | 1.80 (0.29)           | 1.17 (0.29)     | 0.10 (0.04)     |                 |                 |                 |
|           | 20-40  | 1.15 (0.11)           | 0.57 (0.06)     | 0.08 (0.03)     |                 |                 |                 |
|           | 40-60  | 0.91 (0.13)           | 0.55 (0.07)     | 0.08 (0.03)     |                 |                 |                 |
|           | 60-80  | 1.26 (0.33)           | 0.69 (0.13)     | 0.08 (0.03)     |                 |                 |                 |
|           | 80-100 | 1.06 (0.11)           | 1.36 (0.31)     | 0.08 (0.03)     |                 |                 |                 |

\* All numbers in parenthesis are standard error (n=6).

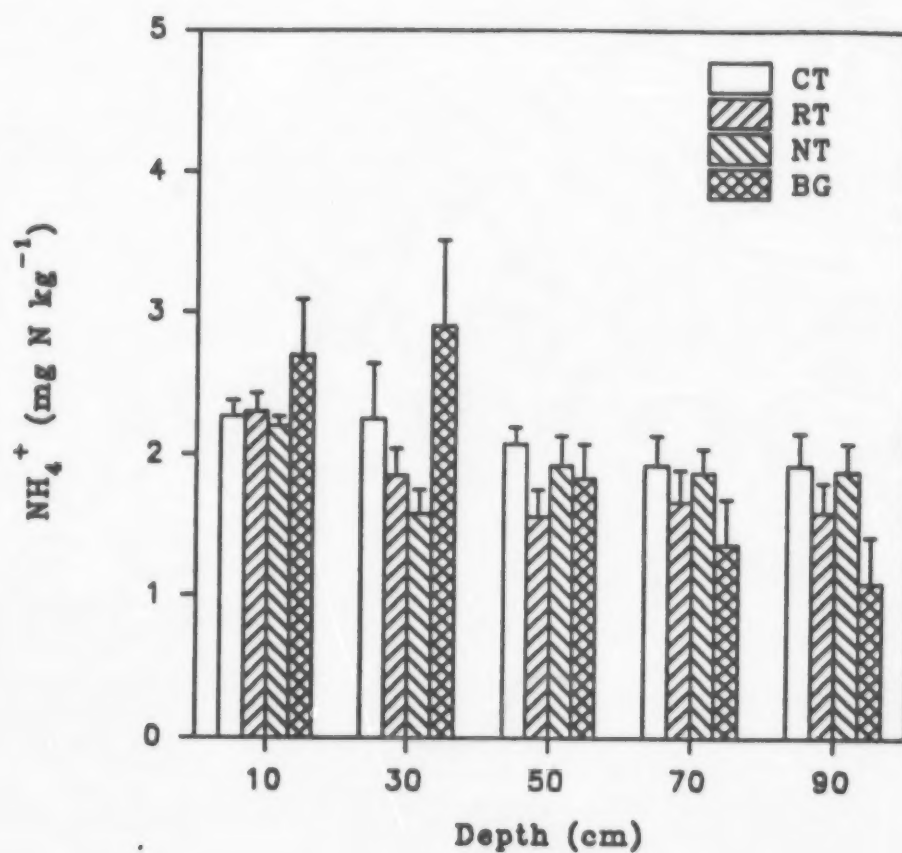


Figure A1. Extractable  $\text{NH}_4^+$  content of the soil for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky bluegrass (BG) treatments in August, 1989.

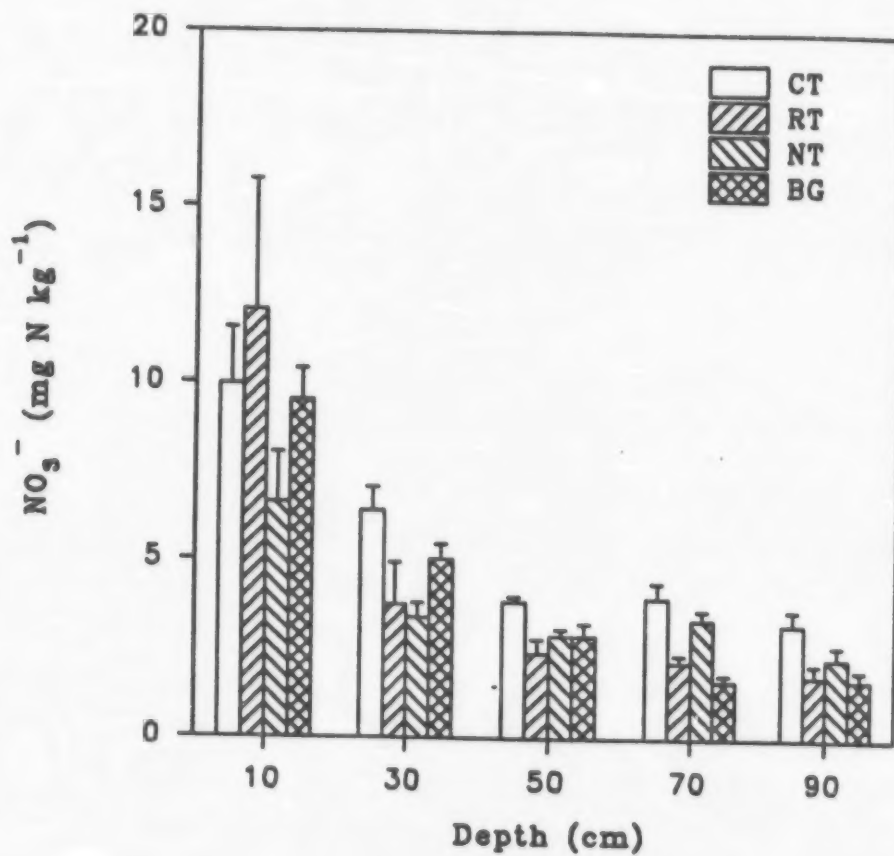


Figure A2. Extractable  $\text{NO}_3^-$  content of the soil for the continuous corn with conventional tillage (CT), ridge tillage (RT), no-till (NT) and Kentucky bluegrass (BG) treatments in August, 1989.

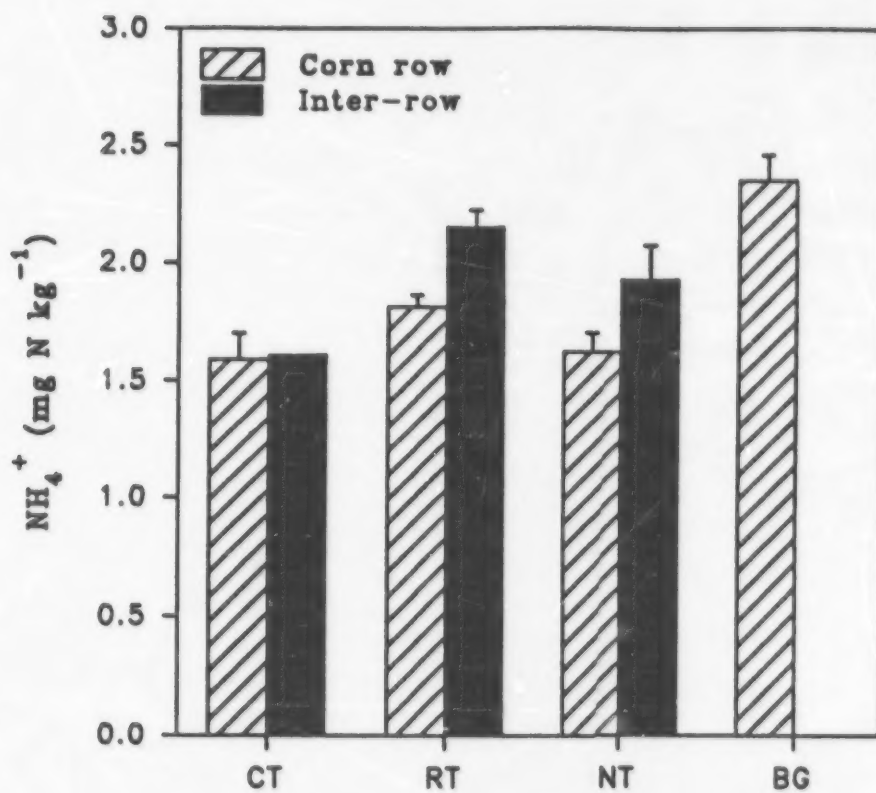


Figure A3. Background  $\text{NH}_4^+$  content 1 day prior to N fertilizer application in soil under conventional tillage (CT), ridge tillage (RT), no-till (NT) corn and Kentucky bluegrass (BG) in 1991.

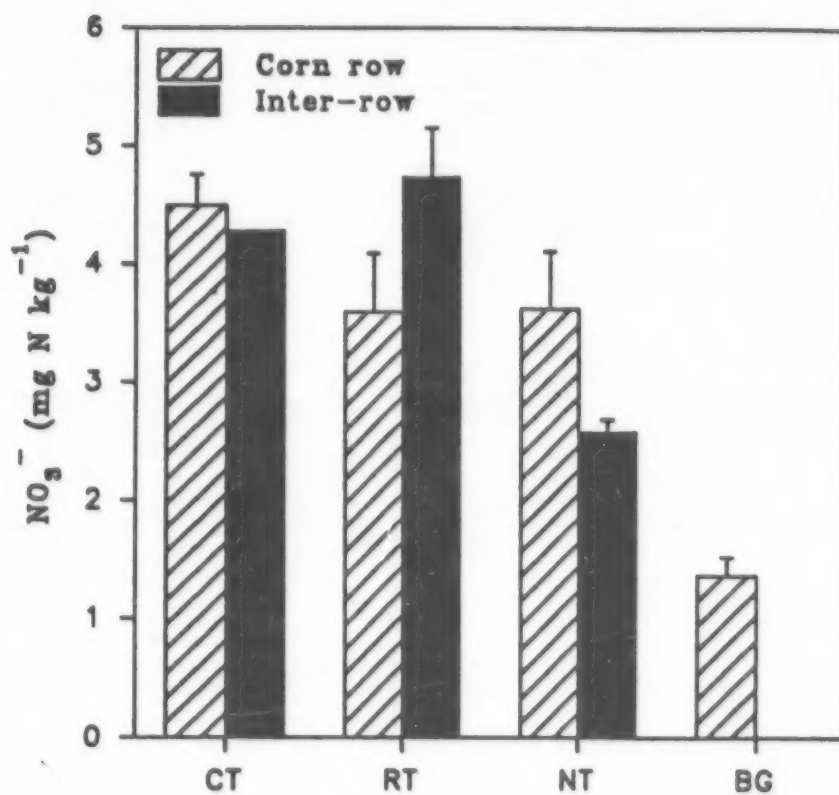


Figure A4. Background  $\text{NO}_3^-$  content 1 day prior to N fertilizer application in soil under conventional tillage (CT), ridge tillage (RT), no-till (NT) corn and Kentucky bluegrass (BG) in 1991.

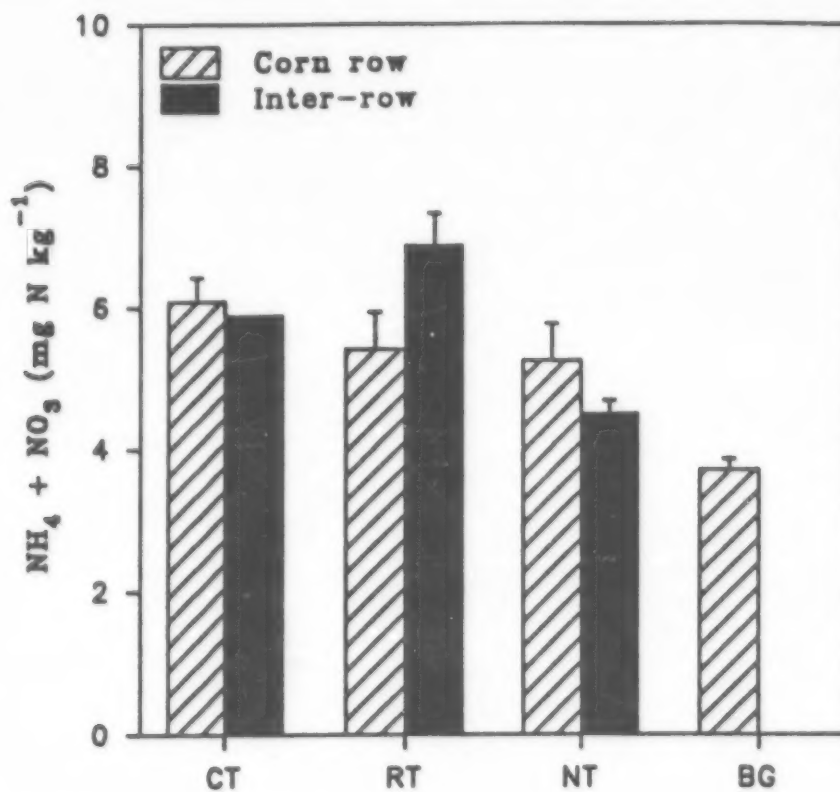


Figure A5. Background  $\text{NH}_4^+ + \text{NO}_3^-$  content 1 day prior to N fertilizer application in soil under conventional tillage (CT), ridge tillage (RT), no-till (NT) corn and Kentucky bluegrass (BG) in 1991.

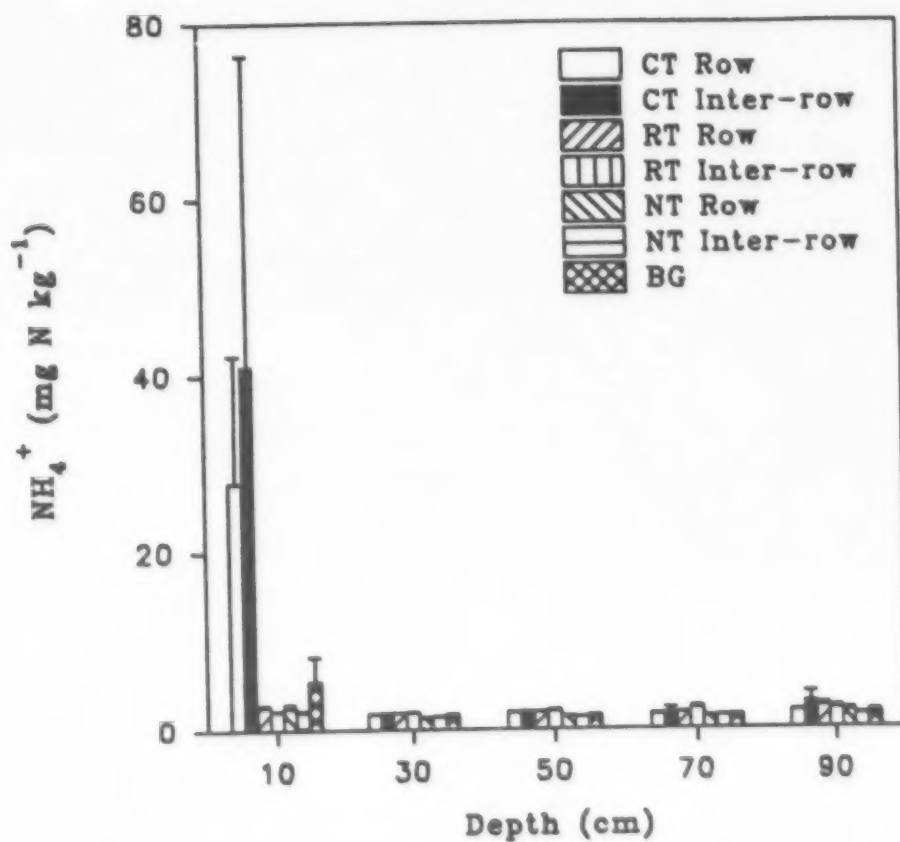


Figure A6. Ammonium content 18 days after N fertilizer application in soil under conventional tillage (CT), ridge tillage (RT), no-till (NT) corn and Kentucky bluegrass (BG) in 1991.

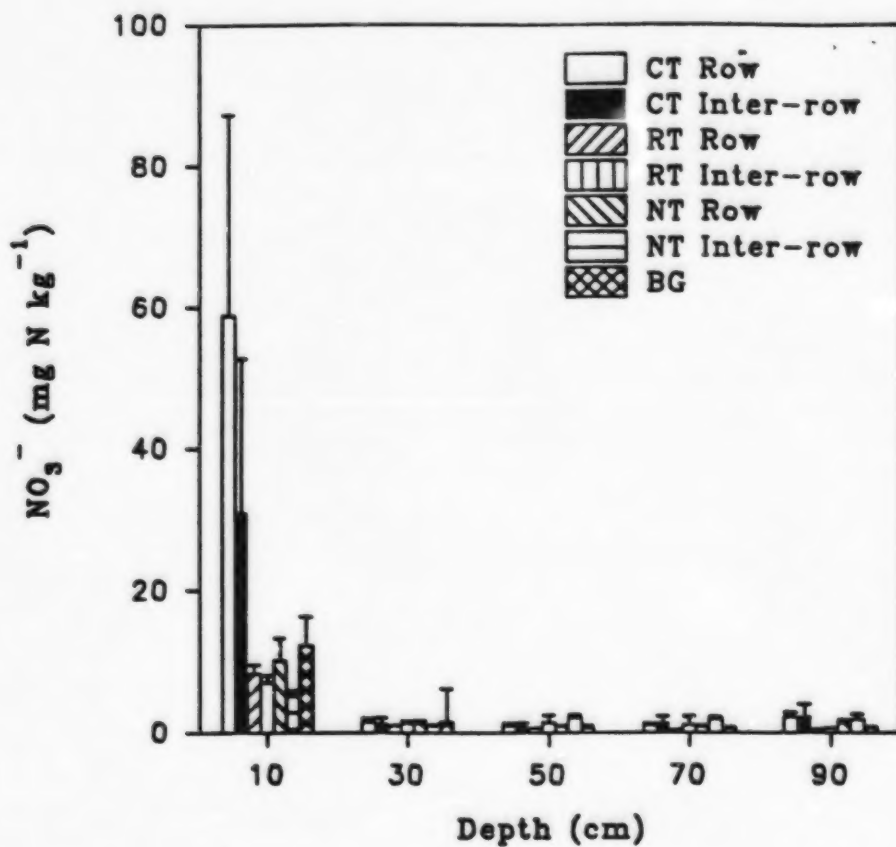


Figure A7. Nitrate content 18 days after N fertilizer application in soil under conventional tillage (CT), ridge tillage (RT), no-till (NT) corn and Kentucky bluegrass (BG) in 1991.

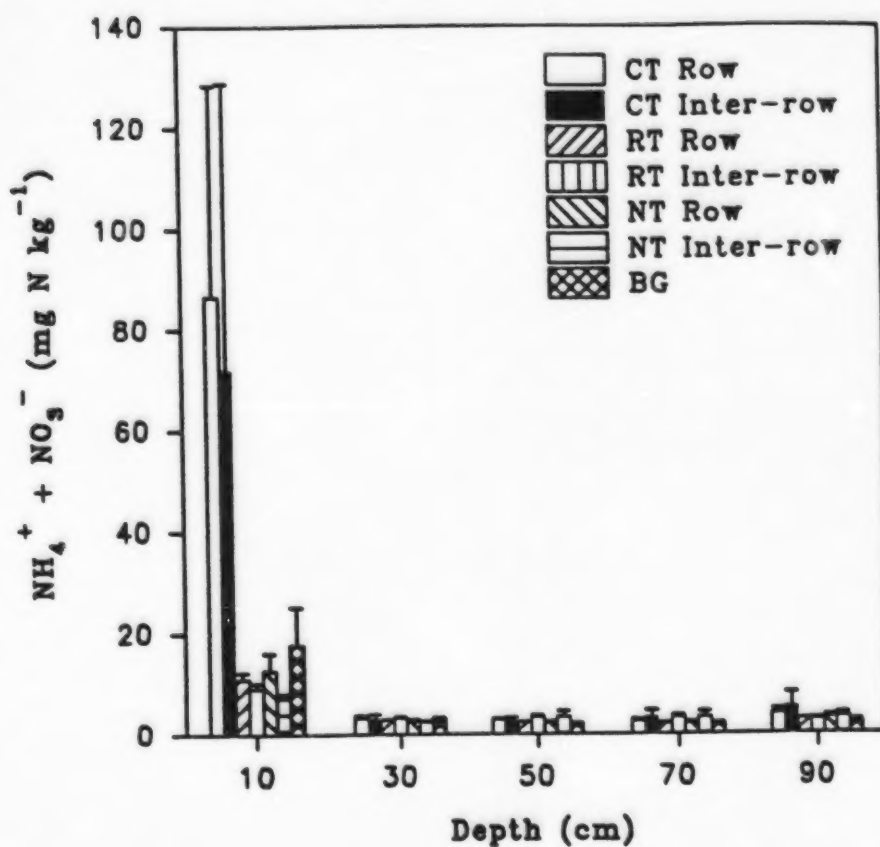


Figure A8. Total  $\text{NH}_4^+ + \text{NO}_3^-$  content 18 days after N fertilizer application in soil under conventional tillage (CT), ridge tillage (RT), no-till (NT) corn and Kentucky bluegrass (BG) in 1991.

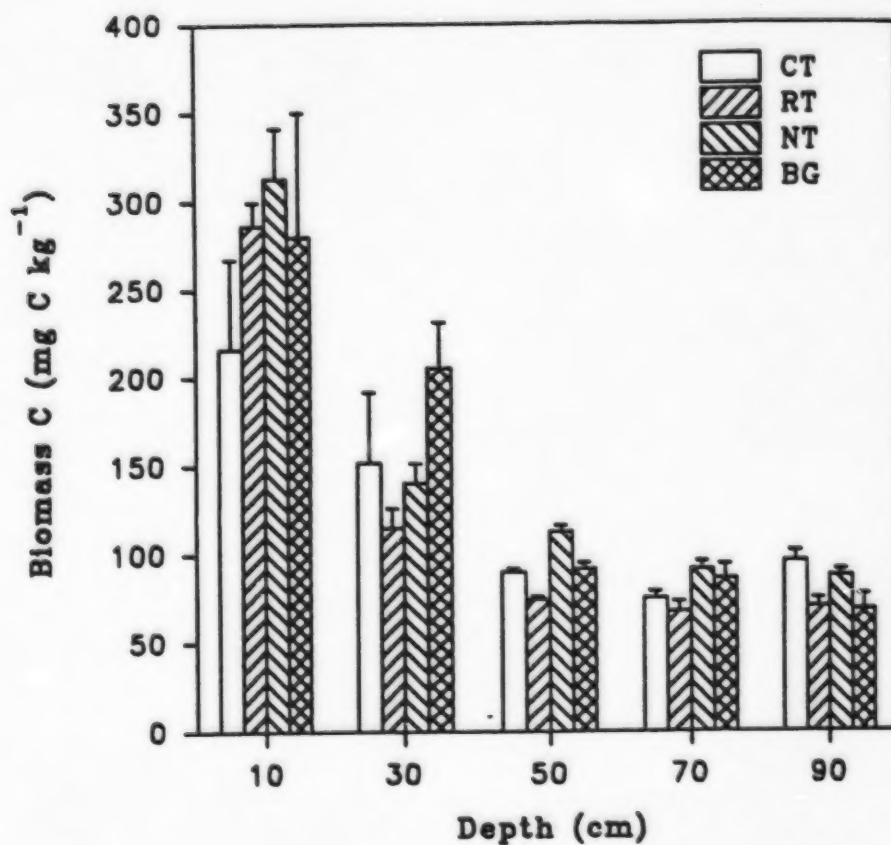


Figure A9. Microbial biomass C content of soil under conventional tillage (CT), ridge tillage (RT), no-till (NT) corn and Kentucky bluegrass (BG) in 1989.